SPACEFLIGHT MECHANICS 2019

Front Cover Images:

This photograph shows the partly-illuminated Earth rising over the lunar horizon. The lunar terrain shown, centered at 85 degrees east longitude and 3 degrees north latitude on the nearside of the Moon is in the area of Smyth's Sea. The Earth is approximately 400,000 km away. Credit: NASA Photo (Apollo 11, AS11-44-6552).

SPACEFLIGHT MECHANICS 2019

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Edited by
Francesco Topputo
Andrew J. Sinclair
Matthew P. Wilkins
Renato Zanetti

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FOREWORD

This volume is the twenty-ninth 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, but recently was changed to every year and the Spaceflight Mechanics was switched to every second year—odd years), Guidance and Control (annual), and International Space Conferences of Pacific-basin Societies (ISCOPS, formerly PISSTA). 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 2019, Volume 168, 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 2019 appears as Volume 168, *Advances in the Astronautical Sciences*. This publication presents the complete proceedings of the AAS/AIAA Space Flight Mechanics Meeting 2019.

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

AAS/AIAA ASTRODYNAMICS VOLUMES

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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 29th Space Flight Mechanics Meeting was held at the Sheraton Maui Resort & Spa in Ka'anapali, Maui, HI from January 13–17, 2019. The meeting was sponsored by the American Astronautical Society (AAS) Space Flight Mechanics Committee and co-sponsored by the American Institute of Aeronautics and Astronautics (AIAA) Astrodynamics Technical Committee. Approximately 286 professionals (including 120 students and 2 retirees) registered for the meeting; attendees included engineers, scientists, and mathematicians representing government agencies, the military services, industry, and academia from the United States and abroad.

A total of 381 abstracts were submitted for the conference, which is a record-breaking number, and finally, 250 technical papers were presented in 28 sessions on topics related to space-flight mechanics and astrodynamics. There were two special sessions on Mars-related missions: "Mars Insight" and "Mars sample return," the former revealing fresh results after the successful landing on Mars occurred on November 26th, 2018.

Unfortunately, the 29th Space Flight Mechanics Meeting was impacted by the US Government shutdown and a delay in processing Visas, which prevented several civil servants and foreign delegates from attending the conference. The meeting introduced a new session on "Artificial Intelligence in Astrodynamics," which got a total of 17 initial submissions. The majority of the papers submitted involved the traditionally crowded topics, such as "Trajectory Design and Optimization" (90 submissions), "Rendezvous and Relative Motion" (44 submission), "Attitude Dynamics and Control" and "Spacecraft Guidance, Navigation, and Control" (31 submission each).

The editors extend their gratitude to all the Session Chairs who ensured the smooth organization of all sessions (in alphabetical order): Roberto Armellin, Juan Arrieta, Marco Ciarcia, Simone D'Amico, Diane Davis, Atri Dutta, Roberto Furfaro, Pradipto Ghosh, Eric Gustafson, Troy Henderson, Sonia Hernandez, Jennifer Hudson, Islam Hussein, Brandon Jones, Thomas Kelecy, Donghoon Kim, Richard Linares, Mauro Massari, Brett Newman, Martin Ozimek, Ryan Park, Marcello Romano, Ryan Russell, Chris Scott, Rohan Sood, Kamesh Subbarao, Nathan Strange, Florian Renk, Mar Vaquero, Roby Wilson, Robyn Woollands, Ryan Woolley.

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

Dr. Francesco Topputo
AAS Technical Chair

Dr. Matthew Wilkins
AAS General Chair

Dr. Andrew Sinclair
AIAA Technical Chair

Dr. Renato Zanetti
AIAA General Chair

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Part II

Part III

ORBIT DETERMINATION AND SPACE SURVEILLANCE TRACKING

Session Chairs:

Session 1: Brandon Jones, University of Texas at Austin

AAS 19-220

ANALYZING FEASIBILITY OF OPTICAL COMMUNICATION OBSERVABLES FOR NAVIGATION

Sarah Elizabeth McCandless* **and Tomas J. Martin-Mur†**

Future deep-space missions are intending to utilize optical communications and thereby take advantage of superior data delivery rates. The same laser-based links could also be used for interplanetary navigation. Two main optical tracking types could be used for this purpose. The first is optical ranging that uses active optical systems at both ends of the link, as opposed to passive systems. The second is optical astrometry, where a telescope images the spacecraft laser against a star background and thereby resolves plane-of-sky position. These data types offer similar capabilities to the radiometric techniques used for current interplanetary missions. These missions have a variety of objectives and requirements, which impacts trajectory determination and the necessary data types. This paper discusses the formulation of the data types and their success in meeting mission requirements for two mission scenarios: a network of spacecraft in orbit about Mars and a spacecraft in a halo orbit at the Earth-Sun L1 Lagrange point. [View Full Paper]

* Navigation Engineer, NASA Jet Propulsion Laboratory, California Institute of Technology, 4800 Oak Grove Drive, Pasadena, California 91109, USA.

† Supervisor, Inner Planet Navigation Group, NASA Jet Propulsion Laboratory, California Institute of Technology, 4800 Oak Grove Drive, Pasadena, California 91109, USA.

NAVIGATION ACCURACY AT JUPITER AND SATURN USING OPTICAL OBSERVATIONS OF PLANETARY SATELLITES[*]

Nicholas Bradley,[†] Shyam Bhaskaran,[‡] Zubin Olikara[§]
and Stephen B. Broschart[**]

Autonomous on-board navigation has the potential to enable new types of missions and decrease reliance on NASA's Deep Space Network for navigation purposes. Previous results have shown that navigating with only optical images of asteroids is feasible for inner planet cruise. In this study, we show that images of natural satellites can be used to navigate during approach and tour phases around the gas giants. We investigate the Jupiter and Saturn systems here, and specifically assess the performance of optical-only navigation for the Juno, Europa Clipper, and Cassini trajectories. Early approach phases and tours at Jupiter would require radiometric data to navigate, but the performance of optical-only data rivals the as-flown performance for Cassini at Saturn. [View Full Paper]

[†] Outer Planet Navigation Group, Mission Design and Navigation Section, Jet Propulsion Laboratory, California Institute of Technology. 4800 Oak Grove Drive, Pasadena, California 91109, USA.

[‡] Group Supervisor, Outer Planet Navigation Group, Mission Design and Navigation Section, Jet Propulsion Laboratory, California Institute of Technology. 4800 Oak Grove Drive, Pasadena, California 91109, USA.

[§] Inner Planet Mission Analysis Group, Mission Design and Navigation Section, Jet Propulsion Laboratory, California Institute of Technology. 4800 Oak Grove Drive, Pasadena, California 91109, USA.

[**] Former member, Outer Planet Navigation Group, Mission Design and Navigation Section, Jet Propulsion Laboratory, California Institute of Technology. 4800 Oak Grove Drive, Pasadena, California 91109, USA. Currently with The Spacing Guild, LLC.

AAS 19-271

ORBIT DETERMINATION SENSITIVITY ANALYSIS FOR THE EUROPA CLIPPER MISSION TOUR

Zahi Tarzi,[*] Dylan Boone,[*] Nickolaos Mastrodemos,[†] Sumita Nandi[*] and Brian Young[‡]

The 2011 Planetary Science Decadal Survey identifies Europa, the fourth largest moon of Jupiter, as the most likely body in the Solar System to harbor extra-terrestrial life.[1] The Europa Clipper mission will orbit Jupiter and investigate Europa's habitability utilizing data collected during multiple close flybys of Europa by a set of five remote sensing and five in-situ instruments. The measurements set is designed to confirm the existence of a subsurface liquid ocean and characterize the thickness of its ice shell. The tour phase of the current mission plan consists of forty-six low altitude Europa science fly-bys. Sufficiently accurate predicted and reconstructed spacecraft orbit determination (OD) is needed to support spacecraft pointing, measurement planning and interpretation of measurements. After briefly discussing expected OD capability, this paper will assess the sensitivity of OD delivery and knowledge performance for the current Europa Mission trajectory through parametric variation of a baseline tour navigation strategy.[2] Variations of several parameters are run, one at a time, to determine the impact on spacecraft ephemeris uncertainties at OD knowledge, delivery, and encounter reconstruction times. There are two basic categories of sensitivity runs considered: variations of tracking data type and amount, and variations to dynamic parameters. The results of these parameter and data variations are compared against the values necessary to achieve accurate instrument pointing and observation planning. [View Full Paper]

[*] Navigation Engineer, Outer Planet Navigation Group, Jet Propulsion Laboratory, California Institute of Technology, 4800 Oak Grove Drive, Pasadena, California 91109, USA.

[†] Navigation Engineer, Solar System Dynamics Group, Jet Propulsion Laboratory, California Institute of Technology, 4800 Oak Grove Drive, Pasadena, California 91109, USA.

[‡] Navigation Engineer, Flight Path Control Group, Jet Propulsion Laboratory, California Institute of Technology, 4800 Oak Grove Drive, Pasadena, California 91109, USA.

RECURSIVE POLYNOMIAL MINIMUM MEAN SQUARE ERROR ESTIMATION WITH APPLICATIONS TO ORBIT DETERMINATION

Simone Servadio[*] and Renato Zanetti[†]

This paper presents a systematic generalization of the linear update structure associated with the extended Kalman filtering for high order polynomial estimation of nonlinear dynamical systems. A minimum mean-square error criterion is used as a cost function to determine the optimal gains required for the estimation process. The high order series representation is implemented effectively using Differential Algebra techniques.

[View Full Paper]

[*] Ph.D. Student, Aerospace Engineering and Engineering Mechanics, The University of Texas at Austin, Texas 78712-1221, USA.
[†] Assistant Professor, Aerospace Engineering and Engineering Mechanics, The University of Texas at Austin, Texas 78712-1221, USA.

AAS 19-507

GEOSTATIONARY SATELLITE ORBIT ACCURACY ANALYSIS FOR MANEUVER EFFICIENCY CALIBRATION

Yoola Hwang* and Byoung-Sun Lee†

Geostationary satellite keeps the position within the control box in order to conduct its missions. As geostationary satellites increase, the control box is restricted into small area. Thus, the position evaluation for the maneuver becomes important factor for the next operation. In this research, we analyze the orbit determination (OD) uncertainty using covariance propagation and measurement residuals for the maneuver efficiency calibration. Both covariance error and measurement residuals depend on measurements noises. The maneuver efficiency is calibrated from the delta velocity of the principal axis between the thruster telemetry information and the estimated OD. [View Full Paper]

* Principal Research Staff, Unmanned Vehicle System Research Team, ETRI, 218 Gajeong-no, Yuseong-gu, 34129, Daejeon, Rep. of Korea. E-mail: ylhwang@etri.re.kr.

† Leader, Principal Research Staff, Unmanned Vehicle System Research Group, ETRI, 218 Gajeong-no, Yuseong-gu, 34129, Daejeon, Rep. of Korea. E-mail: lbs@etri.re.kr.

EXTENDED KALMAN FILTERING IN REGULARIZED COORDINATES FOR ORBIT DETERMINATION

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

The linear error theory used in our previous work developing an extended Kalman filter formulation in Burdet regularized coordinates for the purpose of estimating the unperturbed two-body motion of Earth-orbiting satellites is improved upon. Critical challenges in implementation arise as a result of this formulation and are addressed. Simulated orbit determination is conducted in the regularized space and using a traditional Cartesian extended Kalman filter for comparison. [View Full Paper]

[*] Graduate Student, Department of Aerospace Engineering, The Pennsylvania State University, University Park, Pennsylvania 16802, USA. E-mail: dmc5758@psu.edu. Student Member AAS.
[†] Associate Professor, Department of Aerospace Engineering, The Pennsylvania State University, University Park, Pennsylvania 16802, USA. E-mail: psingla@psu.edu. AAS Fellow, AIAA Associate Fellow.
[‡] Assistant Professor, Department of Aerospace Engineering, Texas A&M University, College Station, Texas 77840, USA. E-mail: mmajji@exchange.tamu.edu. AIAA Senior Member, AAS Member.

INITIAL RELATIVE ORBIT DETERMINATION SOLUTIONS USING POLYNOMIAL SYSTEMS

Troy A. Henderson,[*] T. Alan Lovell,[†] Alex E. Sizemore,[‡] Kenneth R. Horneman[§] and David A. Zuehlke[**]

This paper presents a solution method for the initial relative orbit determination problem using a system of polynomial equations derived from the line-of-sight measurements from an observer spacecraft to a resident space object. The measurement equations are cast as a set of polynomials equal in number to the states governing the relative motion, with the initial conditions of the states as variables. Solving for the roots of the polynomial equations can be performed using various methods. Improved conditioning, through variable and equation scaling, is also explored to increase the likelihood of finding accurate orbit solutions. [View Full Paper]

[*] Assistant Professor, Aerospace Engineering, Embry-Riddle Aeronautical University, 600 S. Clyde Morris Blvd., Daytona Beach, Florida 32114, USA.

[†] Senior Aerospace Engineer, Space Vehicles Directorate, Air Force Research Laboratory, Kirtland AFB, New Mexico 87117-5776, USA.

[‡] Postdoctoral Research Assistant, Space Vehicles Directorate, Air Force Research Laboratory, Kirtland AFB, New Mexico 87117-5776, USA.

[§] Principal Aerospace Engineer, Emergent Space Systems, Kirtland AFB, New Mexico 87117-5776, USA.

[**] Graduate Student, Aerospace Engineering, Embry-Riddle Aeronautical University, Daytona Beach, Florida 32114, USA.

IDENTIFYING SPACECRAFT CONFIGURATION USING DEEP NEURAL NETWORKS FOR PRECISE ORBIT ESTIMATION

Madhur Tiwari,[*] David Zuehlke[†] and Troy A. Henderson[‡]

This paper proposes a method for classifying the configuration of a satellite using convolution neural network (CNN) in Deep Neural Networks. A CNN is created and trained using MATLAB's Neural Net Toolbox based on upsampling and downsampling. The resulting network identifies if the image has a spacecraft. Images are taken with a ground-based telescope, processed, then features are identified and tracked across frames before running angles-only orbit determination (AIOD). AIOD results are analyzed for centroid data of a full extended object vs. features of interests (i.e. central bus and panel).

[View Full Paper]

[*] PhD Candidate, Aerospace Engineering, Embry-Riddle Aeronautical University, 600 S. Clyde Morris Blvd., Daytona Beach, Florida 32114 USA. E-mail: tiwarim@my.erau.edu.

[†] Graduate Student, Aerospace Engineering, Embry-Riddle Aeronautical University, Daytona Beach, Florida 32114, USA.

[‡] Assistant Professor, Aerospace Engineering, Embry-Riddle Aeronautical University, Daytona Beach, Florida 32114, USA.

TRAJECTORY DESIGN AND OPTIMIZATION

Session Chairs:

Session 4: Martin Ozimek, The Johns Hopkins University Applied Physics Laboratory

Session 8: Sonia Hernandez, Jet Propulsion Laboratory

Session 12: Ryan Russell, The University of Texas at Austin

Session 20: Atri Dutta, Wichita State University

Session 24: Roberto Armellin, University of Surrey

Session 28: Pradipto Ghosh, Analytical Graphics, Inc. and Jennifer Hudson, Western Michigan University

The following papers were not available for publication:

AAS 19-226 Paper Withdrawn

AAS 19-330 Paper Withdrawn

AAS 19-361 Paper Withdrawn

AAS 19-426 Paper Withdrawn

AAS 19-477 Paper Withdrawn

AAS 19-500 Paper Withdrawn

AAS 19-201

INDIRECT OPTIMIZATION OF LOW-THRUST TRAJECTORIES USING HOMOTOPY

Bradley Wall*

In this work a homotopic approach is used to start with a simple indirect low-thrust trajectory solution and alter the boundary conditions slowly until the desired trajectory problem is solved. It is shown that the user can change the inclination, semimajor axis, eccentricity, and true anomaly of the target body as well as the transfer time of the trajectory. As previously shown in other works, the thrust acceleration of the spacecraft can then be changed to yield optimal bang-bang control trajectories. [View Full Paper]

* Associate Professor, Aerospace Engineering, Embry-Riddle Aeronautical University, Prescott, Arizona 86301, USA.

MARS 2020 MISSION DESIGN AND NAVIGATION OVERVIEW

Fernando Abilleira,[*] Seth Aaron,[†] Chuck Baker,[‡] Dan Burkhart,[§] Gerhard Kruizinga,[**] Julie Kangas,[††] Mark Jesick,[‡‡] Robert Lange,[§§] Sarah-Elizabeth McCandless,[***] Mark Ryne,[†††] Jill Seubert,[‡‡‡] Sean Wagner[§§§] and Mau Wong[****]

Following the exceptionally successful Mars Science Laboratory mission which placed the Curiosity rover in the interior of Gale Crater in August 2012, NASA will launch the next rover in the 2020 Earth to Mars opportunity arriving to the Red Planet in February 2021 to explore areas suspected of former habitability and look for evidence of past life. This paper details the mission and navigation requirements set by the Project and how the final mission design and navigation plan satisfies those requirements. [View Full Paper]

[*] M2020 Mission Design & Navigation Manager, E-mail: Fernando.Abilleira@jpl.nasa.gov.
[†] M2020 EDL Trajectory Analyst, E-mail: Seth.Aaron@jpl.nasa.gov.
[‡] M2020 Mission Planner, E-mail: Charles.J.Baker@jpl.nasa.gov.
[§] M2020 EDL Trajectory Lead, E-mail: Paul.D.Burkhart@jpl.nasa.gov.
[**] M2020 Navigation Team Lead, E-mail: Gerhard.L.Kruizinga@jpl.nasa.gov.
[††] M2020 Trajectory Lead, E-mail: Julie.A.Kangas@jpl.nasa.gov.
[‡‡] M2020 Orbiter Determination Analyst, E-mail: Mark.C.Jesick@jpl.nasa.gov.
[§§] M2020 Mission System Systems Engineer, E-mail: Robert.D.Lange@jpl.nasa.gov.
[***] M2020 Orbit Determination Analyst, E-mail: Sarah.E.McCandless@jpl.nasa.gov.
[†††] M2020 Orbit Determination Analyst, E-mail: Mark.S.Ryne@jpl.nasa.gov.
[‡‡‡] M2020 Orbit Determination Analyst, E-mail: Jill.Tombasco@jpl.nasa.gov.
[§§§] M2020 Maneuver Analyst, E-mail: Sean.V.Wagner@jpl.nasa.gov.
[****] M2020 Maneuver Lead, E-mail: Mau.C.Wong@jpl.nasa.gov.

Jet Propulsion Laboratory, California Institute of Technology, 4800 Oak Grove Drive, Pasadena, California 91109, USA.

AL YAH 3 RECOVERY AND ORBIT TRANSFER DESIGN*

Marc D. DiPrinzio,† Peter J. Edelman,‡ Gregory Fruth,§ Jose J. Guzman, John W. Hartmann,†† Rosemary C. Huang,‡‡ James W. Gearhart,§§ Demyan V. Lantukh,*** Robert E. Markin††† and Christopher L. Ranieri‡‡‡**

After an Ariane 5 ECA launch anomaly, the Al Yah 3 spacecraft required significantly more fuel to reach its desired GEO mission orbit slot. Northrop Grumman Innovation Systems and The Aerospace Corporation partnered to design an orbit transfer recovery that maximized mission life. By using specialized trajectory optimization tools, a recovery was found that maximized the combined performance of three different propulsion systems. A tool that optimizes the end-to-end transfer was critical to the design process and is shown to produce better results compared to recovery options designed using experience and intuition alone. More than 8 years of Al Yah 3's mission life was salvaged. [View Full Paper]

† Senior Engineering Specialist, Mission Analysis and Operations Department, The Aerospace Corporation, M/S CH1-510, 14301 Sullyfield Circle, Unit C, Chantilly, Virginia 20151-1622, USA.

‡ Member of the Technical Staff, Flight Mechanics Department, The Aerospace Corporation, P.O. Box 92957 M4-942, Los Angeles, California 90009-2957, USA.

§ Director, Flight Mechanics Department, The Aerospace Corporation, P.O. Box 92957 M4-942, Los Angeles, California 90009-2957, USA.

** Engineering Manager, Performance Modeling and Analysis Department, The Aerospace Corporation, M/S CH1-510, 14301 Sullyfield Circle, Unit C, Chantilly, Virginia 20151-1622, USA.

†† Staff Systems Engineer – Science & Exploration Programs, Northrop Grumman Innovation Services, Gilbert, Arizona 85233, USA.

‡‡ Member of the Technical Staff, Flight Mechanics Department, The Aerospace Corporation, P.O. Box 92957 M4-957, Los Angeles, California 90009-2957, USA.

§§ Sr. Manager, Flight Dynamics Group, Northrop Grumman Innovation Systems, Dulles, Virginia 20166, USA.

*** Senior Member of the Technical Staff, Flight Mechanics Department, The Aerospace Corporation, P.O. Box 92957 M4-942, Los Angeles, California 90009-2957, USA.

††† Senior Engineering Specialist, Mission Analysis and Operations Department, The Aerospace Corporation, M/S CH1-510, 14301 Sullyfield Circle, Unit C, Chantilly, Virginia 20151-1622, USA.

‡‡‡ Engineering Manager, Flight Mechanics Department, The Aerospace Corporation, P.O. Box 92957 M4-941, Los Angeles, California 90009-2957, USA.

OPTIMIZATION OF VARIABLE-SPECIFIC-IMPULSE GRAVITY-ASSIST TRAJECTORIES

Zhemin Chi,[*] Di Wu,[†] Fanghua Jiang[‡] and Junfeng Li[§]

This paper presents a series of optimization methods for finding fuel-optimal gravity-assist trajectories that utilize the practical solar electric propulsion with variable specific impulse. An optimization method combining the particle swarm optimization and the indirect method is proposed to optimize the variable-specific-impulse gravity-assist low-thrust trajectories. Additionally, the modified logarithmic homotopy function is applied to serve as a gateway in variable-specific-impulse case. The algorithm for optimization multiple-gravity-assist trajectories is also presented in this paper. Moreover, the experimental data of NASA's Evolutionary Xenon Thruster (NEXT) is employed in numerical simulations. Main-belt asteroids missions are given to substantiate the feasibility of the proposed methods. [View Full Paper]

[*] PhD Candidate, School of Aerospace Engineering, Tsinghua University, 100084 Beijing, China.
[†] PhD Candidate, School of Aerospace Engineering, Tsinghua University, 100084 Beijing, China.
[‡] Associate Professor, School of Aerospace Engineering, Tsinghua University, 100084 Beijing, China.
[§] Professor, School of Aerospace Engineering, Tsinghua University, 100084 Beijing, China.

ON ALIGHTING DAINTILY AT JUPITER: INNOVATIVE METHODS FOR EFFICIENTLY ACHIEVING JOVIAN ORBIT

Timothy P. McElrath,[*] Stefano Campagnola,[†] Anastassios E. Petropoulos,[†] Amanda Haapala[‡] and Fazle E. Siddique[§]

Spacecraft bound for Jupiter orbit typically spend the majority of their ΔV in the capture process. The Galilean satellites provide myriad flyby opportunities to assist in the capture process. In addition, the relatively low solar range (compared to the other outer planets) and absence of significant rings add to the option space. Starting with typical single-flyby and Jupiter Orbit Insertion (JOI) maneuver sequences, we will walk through a range of capture options, including longer post-capture tours, double flybys (and their constraints), combined with solar-electric propulsion (SEP) usage, and finally the potential benefits of retrograde, "cloudtops" orbit insertion. In combination with a ΔV-EGA interplanetary trajectory, the cloudtops arrival saves over 500 m/s in the capture sequence.

[View Full Paper]

[*] Principal Engineer, Mission Design & Navigation Section, Jet Propulsion Laboratory, California Institute of Technology, 4800 Oak Grove Drive, Pasadena, California 91109, USA.

[†] Mission Design Engineer, Mission Design & Navigation Section, Jet Propulsion Laboratory, California Institute of Technology, 4800 Oak Grove Drive, Pasadena, California 91109, USA.

[‡] Mission Design Engineer, Astrodynamics and Controls Group, Johns Hopkins University Applied Physics Laboratory, 11100 Johns Hopkins Road, Laurel, Maryland 20723, USA.

[§] Mission Design and Navigation Engineer, Astrodynamics and Controls Group, Johns Hopkins University Applied Physics Laboratory, 11100 Johns Hopkins Road, Laurel, Maryland 20723, USA.

AAS 19-245

HIGH-PERFORMANCE INTERPOLATION OF CHEBYSHEV EPHEMERIDES

Juan Arrieta*

I describe a computationally-efficient method to interpolate ephemerides that are provided as truncated Chebyshev series. It increases throughput by a factor of 10 to 100, is thread-safe, and does not sacrifice accuracy. The methodology and approach are meant for use cases where strict adoption of SPICE ephemerides is required and ephemerides interpolation is proven to be a computational bottleneck or thread-safe access is desired. [View Full Paper]

* Founder and CEO, Nabla Zero Labs, 177 East Colorado Blvd., Suite 2025, Pasadena, California 91105, USA.
E-mail: juan.arrieta@nablazerolabs.com.

AAS 19-248

TRANSFERS BETWEEN PLANAR AND THREE-DIMENSIONAL QUASI SATELLITE ORBITS IN THE VICINITY OF PHOBOS

Elisabet Canalias,[*] Laurence Lorda[*] and Enne Hekma[†]

The exploration of the Martian moons has always raised interest from the scientific community and the space agencies. JAXA's MMX mission (for Mars Moons eXploration) is expected to visit Phobos and Deimos in the mid 2020s. The French space agency (CNES) participates in the mission analysis studies of this mission, in particular for the Phobos proximity phase. Moreover, the Martian moons provide a very challenging environment for trajectory design, requiring sophisticated techniques. Quasi satellite orbits (QSO), also known as distant retrograde orbits, have been identified as a means to orbit Phobos in the sense of formation flying. In order to satisfy the scientific and operational requirements of an exploration mission of this kind, several different QSO trajectories may have to be included in the baseline scenario. The present paper deals with the transfer problem between planar QSO trajectories, which stay inside the orbital plane of the moon around Mars, and 3-dimensional QSOs, allowing for the exploration of higher latitudes. The one impulse transfer strategy that has been implemented by the authors will be presented, from the preliminary approximations in simple dynamical models up to the transfer trajectories adjusted in realistic dynamics. [View Full Paper]

[*] CNES, 18 Av. Edouard Belin, 31400 Toulouse, France.
[†] Thales Services, 290 Allée du Lac, 31670 Labège, France.

THE IMPLEMENTATION OF MAXIMUM LIKELIHOOD ESTIMATION IN SPACE LAUNCH SYSTEM VEHICLE DESIGN

W. B. Stein,* S. B. Thompson,† T. L. Statham‡ and A. S. Craig§

The Space Launch System uses a Maximum Likelihood Estimation process in conjunction with Design of Experiments to develop statistically representative vehicles for the Block 1 configuration. These vehicles are the used to estimate maximum load conditions for simulating stressing cases in other simulations. This paper discusses the modeling process and how SLS captures manufacturing uncertainty in the launch vehicle design. It also provides an overview of the differences between Block 1 statistical representations. This paper also discusses proper grid choice as well as which uncertainties drive the vehicle design. [View Full Paper]

* Propulsion Science Tech Fellow, Guidance, Navigation, and Mission Analysis Branch, Jacobs Space Exploration Group, Huntsville, Alabama 35812, USA. E-mail: william.b.stein@nasa.gov.

† GNC Engineer, Guidance, Navigation, and Mission Analysis Branch, Troy 7, Jacobs Space Exploration Group, Huntsville, Alabama 35812, USA. E-mail: seth.b.thompson@nasa.gov.

‡ GN&C Systems Engineer, Guidance, Navigation, and Mission Analysis Branch, Jacobs Space Exploration Group, Huntsville, Alabama 35812, USA. E-mail: tamara.l.statham@nasa.gov.

§ Aerospace Vehicle Engineer, Guidance, Navigation, and Mission Analysis Branch, NASA George C. Marshall Space Flight Center, Huntsville, Alabama 35812, USA. E-mail: scott.craig@nasa.gov.

AAS 19-255

TUBE STOCHASTIC OPTIMAL CONTROL FOR NONLINEAR CONSTRAINED TRAJECTORY OPTIMIZATION PROBLEMS

Naoya Ozaki,[*] Stefano Campagnola[†] and Ryu Funase[‡]

Recent low-thrust space missions have highlighted the importance of designing trajectories that are robust against uncertainties. In its complete form, this process is formulated as a nonlinear constrained stochastic optimal control problem. This problem is among the most complex in control theory, and no practically applicable method to low-thrust trajectory optimization problems has been proposed to date. This paper presents a new algorithm to solve stochastic optimal control problems with nonlinear systems and constraints. The proposed algorithm uses the unscented transform to convert a stochastic optimal control problem into a deterministic problem, which is then solved by trajectory optimization methods such as differential dynamic programming. Two numerical examples, one of which applies the proposed method to low-thrust trajectory design, illustrate that it automatically introduces margins that improve robustness. Finally, Monte Carlo simulations are used to evaluate the robustness and optimality of the solution.

[View Full Paper]

[*] Ph.D., Department of Space Flight Systems, Institute of Space and Astronautical Science, Japan Aerospace Exploration Agency, Kanagawa 252-5210, Japan. E-mail: naoya.ozaki@ac.jaxa.jp.
[†] Mission Design Engineer, Outer Planet Mission Analysis Group, Jet Propulsion Laboratory, California Institute of Technology, Pasadena, California 91109, USA.
[‡] Ph.D., Associate Professor, Department of Aeronautics and Astronautics, The University of Tokyo, 7-3-1, Hongo, Bunkyo-ku, Tokyo, 113-8656, Japan.

DESIGNING LOW-ENERGY TRANSFERS FROM LOW-EARTH ORBIT TO A TEMPORARILY-CAPTURED ORBITER

Kanta Yanagida,[*] Naoya Ozaki[†] and Ryu Funase[‡]

Temporarily-captured orbiters (TCOs) are a new population of asteroids that are temporarily gravitationally bound around the Earth-Moon system. Because of its small geocentric distance and energy, short-term exploration with small Δv is expected possible. This study aims to construct low-energy transfers to 2006 RH120, one of the TCOs, from low-Earth orbit using an analogy with the Earth-Moon low-energy transfers. The initial guess was sought by back-propagating perturbed 2006 RH120's trajectory, then it was optimized through the direct multiple shooting method. The result shows that various transfers are possible with rendezvous Δv below 100 m/s, and they form diverse family structures. [View Full Paper]

[*] Graduate Student, Department of Aeronautics and Astronautics, the University of Tokyo, 7-3-1, Hongo, Bunkyo-ku, Tokyo, 113-8656, Japan. E-mail: yanagida@space.t.u-tokyo.ac.jp.
[†] Ph.D., Department of Space Flight Systems, Japan Aerospace Exploration Agency, Kanagawa 252-5210, Japan.
[‡] Ph.D., Associate Professor, Department of Aeronautics and Astronautics, the University of Tokyo, 7-3-1, Hongo, Bunkyoku, Tokyo, 113-8656, Japan.

A TITAN GRAVITY-ASSIST TECHNIQUE FOR BALLISTIC TOURS SKIMMING OVER THE RINGS OF SATURN

Mar Vaquero,[*] Juan Senent[†] and Matthew Tiscareno[‡]

A novel type of Titan-flyby orbits featuring passes of the Saturn rings at close range has been recently discovered. The purpose of this study is to explore the trajectory design space and assess the applicability of such orbits to the design of a Saturn Ring Tour mission concept. A set of initial conditions required to start a tour of the rings is first determined and a flyby sequence to maximize the science observation time over desired ring regions in terms of distance, relative velocity and duration is then selected. To demonstrate the potential of this technique, a sample high-fidelity ballistic ring tour is detailed. [View Full Paper]

[*] Mission Design Engineer, NASA Jet Propulsion Laboratory, California Institute of Technology, Pasadena, California 91109, USA.

[†] Engineering Applications Software Engineer, NASA Jet Propulsion Laboratory, California Institute of Technology.

[‡] Senior Research Scientist, Carl Sagan Center for the Study of Life in the Universe, SETI Institute, Mountain View, California 94043, USA.

Pre-decisional information, for planning and discussion only.

ROBUST OPTIMISATION OF LOW-THRUST INTERPLANETARY TRANSFERS USING EVIDENCE THEORY

Marilena Di Carlo,[*] Massimiliano Vasile,[†] C. Greco[‡] and R. Epenoy[§]

This work presents the formulation and solution of optimal control problems under epistemic uncertainty, when this uncertainty is modelled with Dempster-Shaffer theory of evidence. The application is to the design of low-thrust interplanetary transfers when an epistemic uncertainty exists in the performance of the propulsion system and in the magnitude of the departure hyperbolic excess velocity. The problem is solved by transforming the exact formulation, that uses discontinuous Belief functions, into an inexact formulation that uses a new continuous statistical function, called S in the following, that approximates the value of the Belief function. The optimisation is realised by first building a surrogate model of the quantities of interest and associated S functions. The surrogate is then progressively updated as the optimisation proceeds. The proposed method is applied to the design of optimal low-thrust transfers from the Earth to asteroid Apophis.

[View Full Paper]

[*] Research Associate, Department of Mechanical and Aerospace Engineering, University of Strathclyde, 75 Montrose Street, G1 1XJ, Glasgow, United Kingdom.
[†] Professor, Department of Mechanical and Aerospace Engineering, University of Strathclyde, 75 Montrose Street, G1 1XJ, Glasgow, United Kingdom.
[‡] PhD Student, Department of Mechanical and Aerospace Engineering, University of Strathclyde, 75 Montrose Street, G1 1XJ, Glasgow, United Kingdom.
[§] Engineer, CNES, 18 avenue Edouard Belin 31401 Toulouse Cedex 9, France.

CHARTING A COURSE TO THE SUN: FLIGHT PATH CONTROL FOR PARKER SOLAR PROBE

Powtawche N. Valerino,* Paul Thompson,† Drew Jones,‡ Troy Goodson,‡ Rob Haw,‡ Eunice Lau,‡ Neil Mottinger‡ and Mark Ryne‡

The successful launch of the Parker Solar Probe (PSP) on August 12, 2018 with a Delta IV rocket and Star-48BV third stage has placed the spacecraft on a 7-year trajectory to study the Sun. The goals of PSP are to better characterize our solar environment and advance our understanding of the Sun at 9.86 Rs. A total of 42 trajectory correction maneuvers are planned. This paper documents trajectory correction maneuver analysis performed just prior to launch until just past the first solar encounter. The pre-launch analysis culminated in two final design cycles which analyzed 24 reference trajectories.

[View Full Paper]

* Corresponding Author. E-mail: Powtawche.Valerino@jpl.nasa.gov; Address: Jet Propulsion Laboratory, California Institute of Technology, 4800 Oak Grove Drive, Pasadena, California 91109, USA.
† Parker Solar Probe Navigation Team Chief, Jet Propulsion Laboratory, California Institute of Technology.
‡ Navigation Engineer, Jet Propulsion Laboratory, California Institute of Technology.

AAS 19-295

MARS GRAVITY ASSIST OPTIONS TO REDUCE MISSION ΔV FOR EUROPA LANDER

Amanda Haapala,[*] Fazle Siddique[†] and Timothy McElrath[‡]

For the Europa Lander concept, a Carrier spacecraft transports a Lander to the Jovian moon Europa to perform in-situ science aimed at detecting bio-signatures. Launch would be in 2026 using the SLS Block-1B to accommodate the mass of the Carrier and Lander. A 2026 baseline launch offers the opportunity for a unique set of Mars gravity assists (MGAs) for both baseline and backup launch options. By exploiting MGAs during interplanetary cruise, cruise ΔV is reduced from 1.6 to 1.3 km/s, and the spacecraft wet mass is correspondingly reduced. Strategies to further reduce ΔV by modifying the Jupiter system entry sequence are explored and enable reduction of total mission ΔV from 2.3 to 1.875 km/s. [View Full Paper]

[*] Mission Design Engineer, Astrodynamics and Controls Group, Johns Hopkins University Applied Physics Laboratory, 11100 Johns Hopkins Rd, Laurel, Maryland 20723, USA.
[†] Mission Design and Navigation Engineer, Astrodynamics and Controls Group, Johns Hopkins University Applied Physics Laboratory, 11100 Johns Hopkins Road, Laurel, Maryland 20723, USA.
[‡] Principal Engineer, Mission Design and Navigation Section, Jet Propulsion Laboratory, California Institute of Technology, 4800 Oak Grove Drive, Pasadena, California 91109, USA.

A SURVEY OF THE METHODS AVAILABLE FOR THE DESIGN OF MANY-REVOLUTION LOW-THRUST PLANETOCENTRIC TRAJECTORIES

Pradipto Ghosh*

The mission use of electric propulsion (EP) systems providing continuous, low thrust has steadily increased over the past several years. As EP technology continues to mature, the upward trend in its efficient utilization is expected to persist. A particularly challenging and long-studied low-thrust trajectory design problem is Electric Orbit Raising, i.e. the design of many-revolution, long duration transfers in the planetocentric space. Numerous methods, both analytical and numerical, optimal and sub-optimal, open-and-closed-loop, and involving models of various degrees of complexity, have been proposed. This paper attempts to characterize and classify the more popular of these methods and their variants. [View Full Paper]

* Astrodynamics Engineer, Analytical Graphics Inc., Exton, Pennsylvania 19341-2380, USA.
E-mail: pghosh@agi.com. Senior Member, AIAA.

JULIA LANGUAGE 1.0 EPHEMERIS AND PHYSICAL CONSTANTS READER FOR SOLAR SYSTEM BODIES

Kaela Martin,[*] Julia Mihaylov,[†] Renee Spear[‡] and Damon Landau[§]

An ephemeris reader in the Julia Language that includes small bodies, asteroid shape modeling, and higher order spherical harmonics is presented here. The second generation of this ephemeris reader introduces shape models of known asteroids as well as spherical harmonics capabilities to support gravitational potential models. This version of the ephemeris reader is also compatible with Julia 1.0 which was released in August of 2018. This second-generation version continues to support the obtainment of critical information needed for mission and trajectory design faster and with added efficiency.

[View Full Paper]

[*] Assistant Professor, Aerospace Engineering, Embry-Riddle Aeronautical University, 3700 Willow Creek Road, Prescott, Arizona 86301, USA.

[†] Student, Aerospace Engineering, Embry-Riddle Aeronautical University, 3700 Willow Creek Road, Prescott, Arizona 86301, USA.

[‡] Student, Aerospace Engineering, Embry-Riddle Aeronautical University, 3700 Willow Creek Road, Prescott, Arizona 86301, USA.

[§] Mission Formulation Engineer, Project Systems Engineering and Mission Formulation Group, Jet Propulsion Laboratory, California Institute of Technology, Pasadena, California 91109, USA.

AAS 19-299

MULTI-STEP OPTIMIZATION OF ORBIT RAISING TRAJECTORIES FOR ALL-ELECTRIC PROPULSION GEOSTATIONARY SATELLITES

Kentaro Nishi,[*] Satoru Ozawa[†] and Saburo Matunaga[‡]

An all-electric propulsion satellite has become a major system architecture for geostationary communication satellites. To mitigate the drawbacks caused by its low-thrust, such as a long stay in a severe radiation environment, minimum-time transfer is necessary. In this paper, we propose a multi-step optimization of orbit raising trajectories for all-electric propulsion satellites. This method splits the problem into multiple steps and optimizes the thrust-vector direction in each step. It lightens the computational load and requires no initial guess. This paper describes the method in detail and evaluates its optimality. It also provides numerical results and a comparison with an existing method. [View Full Paper]

[*] Researcher, Research and Development Directorate, Japan Aerospace Exploration Agency, 2-1-1, Sengen, Tsukuba, Ibaraki, 305-8505 Japan.

[†] Senior Researcher, Research and Development Directorate, Japan Aerospace Exploration Agency, 2-1-1, Sengen, Tsukuba, Ibaraki, 305-8505 Japan.

[‡] Professor, Department of Mechanical Engineering, Tokyo Institute of Technology, 2-12-1, Ookayama, Meguro, Tokyo, 152-8552, Japan.

REACHABLE DOMAIN OF CONTINUOUS LOW-THRUST TRAJECTORIES WITH LINEARIZED DYNAMIC MODEL

Zhaowei Wang* and Fanghua Jiang†

An analytical method is improved for reachable domain of noncircular orbit propelled by low thrust within fixed allowable transfer time, using the linearized differential equations of relative motion. The projection of the relative reachable domain for noncircular and non-coplanar orbits can be obtained by numerical calculation of the derived analytical expressions. A geometrical construction technique based on the envelope theory of family of surfaces is developed to determine the envelope of the reachable domain. A nonlinear programming approach is also applied to solve the reachable domain problem effectively, which comes to be equivalent to the former method. Two numerical examples demonstrate the usefulness of the proposed methods and show that the reachable domains consist well with the ones obtained by numerical optimal control method.

[View Full Paper]

* Ph.D. Candidate, School of Aerospace Engineering, Tsinghua University, 10084 Beijing, China.
† Corresponding Author, Associate Professor, School of Aerospace Engineering, Tsinghua University, 10084 Beijing, China.

OPTIMAL HYPERBOLIC RENDEZVOUS TRAJECTORIES FOR CYCLER MISSIONS*

Mauro Pontani†

Cycler mission architectures are based on the joint use of a large spacecraft that cycles continuously between Earth and Mars, and small taxi vehicles, aimed at connecting each planet with the cycling vessel. The latter describes a hyperbolic path relative to the Earth. This work considers the problem of optimizing the trajectory of the taxi leading to rendezvous with the cycler. Propellant minimizing transfers have been found for both impulsive (short-duration, high-thrust) and low-thrust hyperbolic rendezvous. For the impulsive case, two, three, or four velocity changes are proven to be optimal for performing the rendezvous. If the time of flight can be large, the most fuel efficient rendezvous path is composed of four velocity impulses, and ends at the farthest allowed point along the cycler hyperbola. The optimal low-thrust rendezvous trajectory is found as well, using nonsingular equinoctial elements, in conjunction with the indirect heuristic method.
[View Full Paper]

† Assistant Professor, Department of Astronautical, Electrical, and Energy Engineering, Sapienza University of Rome, via Salaria 851, 00138 Rome, Italy.

ADJOINT ESTIMATION METHOD FOR LOW-THRUST MULTIREVOLUTION TRAJECTORY OPTIMIZATION

Di Wu,* Hexi Baoyin† and Junfeng Li‡

The homotopic approach solves the fuel-optimal problem of low-thrust trajectory by starting from the related and easier energy-optimal problem. However, suitable initial guesses of the adjoint variables should be provided to initialize the solving process of the homotopic method. This paper presents an adjoint estimation method, which would provide the approximate initial guesses for the optimization of low-thrust multirevolution trajectories. Originally, the initial adjoint variables are estimated by solving the optimal control problem of a simplified time-independent dynamical model. The simplified time-independent dynamical model is then linearized around the nominal trajectory, through neglecting the thrust magnitude constraint and the transfer time constraint. Based on the initial adjoint variables analytically obtained, an algorithm is proposed to solve the fuel-optimal control problem of the original model. The effectiveness and efficiency of the proposed method are validated through a numerical simulation of the rendezvous mission from the Earth to the asteroid Dionysus. [View Full Paper]

* Doctor Candidate, School of Aerospace Engineering, Tsinghua University, 100084 Beijing, China.
E-mail: wud17@mails.tsinghua.edu.cn.
† Professor, School of Aerospace Engineering, Tsinghua University, 100084 Beijing, China.
E-mail: baoyin@tsinghua.edu.cn.
‡ Corresponding Author, Professor, School of Aerospace Engineering, Tsinghua University, 100084 Beijing, China.
E-mail: lijunf@tsinghua.edu.cn.

LOW-ENERGY TRAJECTORIES AS STAGING POINTS FOR LANDING ON THE SECONDARY BODY IN THE CR3BP

Luke Bury[*] and Jay McMahon[†]

At low energies with respect to L_1 and L_2 in the Circular Restricted Three Body Problem, regions of possible motion, or necks, appear around these Lagrange points, allowing spacecraft to pass into or out of the interior region. In this study, grid searches of initial conditions are performed across these necks at various energies. These trajectories are propagated forward in time, and those that impact secondary bodies - Europa and Enceladus in this study - are tracked and categorized by impact region, impact angle, area of origin in the neck, and time of flight. At sufficiently low energies, large regions of the secondary surface are ballistically unreachable, and consideration of these bounds with respect to energy and angular momentum is given. The sensitivity of the impact-mappings to changes in the dynamic model are also studied by accounting for J_2 in the Jupiter-Europa system. [View Full Paper]

[*] PhD Precandidate, Ann and H.J. Smead Aerospace Engineering Sciences, The University of Colorado Boulder, 2598 Colorado Ave., Boulder, Colorado 80302, USA.
[†] Assistant Professor, Ann and H.J. Smead Aerospace Engineering Sciences, The University of Colorado Boulder, 2598 Colorado Ave, Boulder, Colorado 80302, USA.

AAS 19-323

MODELING AND OPTIMIZATION OF AERO-BALLISTIC CAPTURE

Carmine Giordano* and Francesco Topputo†

In this paper a novel paradigm for Mars missions is modeled and optimized. This concept consists in a maneuver that combines aerocapture and ballistic capture upon Mars arrival, and is labelled aero-ballistic capture. The idea is reducing the final mass by exploiting the interaction with the planet atmosphere as well as the Sun–Mars gravitational field. The aero-ballistic capture paradigm is formulated. Then the problem is stated by using optimal control theory, and optimal solutions are sought. An assessment of aero-ballistic capture shows the superiority compared to classical maneuvers when medium-to-high final orbits are wanted. [View Full Paper]

* PhD Candidate, Department of Aerospace Science and Technology, Politecnico di Milano, Milan, Italy.
† Assistant Professor, Department of Aerospace Science and Technology, Politecnico di Milano, Milan, Italy.

AAS 19-324

AUTOMATING TOUR DESIGN WITH APPLICATIONS FOR A EUROPA LANDER

Kaela Martin,[*] Damon Landau,[†] Stefano Campagnola,[‡] Reza Karimi,[§] Etienne Pellegrini[**] and Timothy McElrath[††]

Creating a tour design can involve a great deal of trial and error to produce a viable end-to-end trajectory. This paper highlights a new methodology which starts with a broad-search patched-conics tool and ends with an integrated optimizer. The tool is applied to a potential Europa Lander starting at the second Ganymede flyby and ending with the first Europa flyby to produce a trajectory option for a 2033 landing date. [View Full Paper]

[*] Assistant Professor, Aerospace Engineering, Embry-Riddle Aeronautical University, 3700 Willow Creek Road, Prescott, Arizona 86301, USA.
[†] Mission Formulation Engineer, Project Systems Engineering and Mission Formulation Section, Jet Propulsion Laboratory, California Institute of Technology, Pasadena, California 91109, USA.
[‡] Senior Engineer, Outer Planet Mission Analysis Group, Mission Design and Navigation Section, Jet Propulsion Laboratory, California Institute of Technology, Pasadena, California 91109, USA.
[§] Navigation Engineer, Outer Planet Mission Analysis Group, Mission Design and Navigation Section, Jet Propulsion Laboratory, California Institute of Technology, Pasadena, California 91109, USA.
[**] Mission Design Engineer, Outer Planet Mission Analysis Group, Mission Design and Navigation Section, Jet Propulsion Laboratory, California Institute of Technology, Pasadena, California 91109, USA.
[††] Navigation Engineer, Mission Design and Navigation Section, Jet Propulsion Laboratory, California Institute of Technology, Pasadena, California 91109, USA.

AAS 19-327

EUROPA LANDER TRAJECTORY DESIGN: CASE STUDIES FOR THE DIRECT-TO-EARTH ARCHITECTURE

Stefano Campagnola,[*] Tim McElrath,[†] Aline Zimmer[‡] and Damon Landau[§]

This paper presents interesting phasing problems that came up in support of design studies for a potential Europa Lander mission. Recent system trades were performed after the Mission Concept Review in fall 2017, when the NASA board recommended the Europa Lander project design a Direct-to-Earth architecture, i.e. where the Lander would communicate directly to the Earth, without data relay from the carrier vehicle.

Two studies in particular required an original trajectory design concept. In the first study, which considered a bi-propellant system for the lander, we designed an ultra- low-radiation endgame with separate Europa orbit insertion (EOI) and de-orbiting maneuvers for the Descent Vehicle (DOV), and a ballistic Ganymede-impact transfer for the carrier. In the second study, we analyzed trajectories to use Clipper as a data-relay spacecraft during Europa landing. [View Full Paper]

[*] Mission Design Engineer, Mission Design and Navigation Section, Jet Propulsion Laboratory, California Institute of Technology, 4800 Oak Grove Drive, Pasadena, California 91109, USA. E-mail: stefano.campagnola@jpl.nasa.gov.

[†] Principal Engineer, Mission Design and Navigation Section, Jet Propulsion Laboratory, California Institute of Technology, 4800 Oak Grove Drive, Pasadena, California 91109, USA.

[‡] System Engineer, Project Systems Engineering and Formulation Section, Jet Propulsion Laboratory, California Institute of Technology, 4800 Oak Grove Drive, Pasadena, California 91109, USA.

[§] System Engineer, Project Systems Engineering and Formulation Section, Jet Propulsion Laboratory, California Institute of Technology, 4800 Oak Grove Drive, Pasadena, California 91109, USA.

TRAJECTORY DESIGN USING QUASI-PERIODIC ORBITS IN THE MULTI-BODY PROBLEM

Brian P. McCarthy* **and Kathleen C. Howell†**

Incorporating quasi-periodic orbits (QPOs) into the preliminary design process offers a wider range of options to meet mission constraints and address the challenges in a complex trade space. In this investigation, QPO stability and alternative QPO family continuation schemes are examined to meet various types of trajectory constraints. Additionally, trajectory arcs from QPOs are exploited to generate transfers between periodic orbits. By leveraging the natural dynamical structures associated with QPOs, novel low cost transfers emerge. [View Full Paper]

* Ph.D. Student, School of Aeronautics and Astronautics, Purdue University, West Lafayette, Indiana 47907, USA. E-mail: mccart71@purdue.edu.
† Hsu Lo Distinguished Professor of Aeronautics and Astronautics, School of Aeronautics and Astronautics, Purdue University, West Lafayette, Indiana 47907, USA. E-mail: howell@purdue.edu.

AAS 19-331

NASA EXPLORATION MISSION 2 MISSION DESIGN

A. S. Craig,[*] C. F. Berry,[†] M. D. Bjorkman,[‡] E. L. Christiansen,[§] G. L. Condon,[**] A. R. Harden,[††] J. K. Little,[‡‡] T. Perryman[§§] and S. B. Thompson[***]

Exploration Mission 2 (EM-2) will be NASA's first manned flight on the Space Launch System (SLS) and Orion Spacecraft. The mission has been changed from an SLS Block 1B configuration to Block 1. This change has necessitated a reexamination of the flight profile to determine what changes must be made in order to accommodate the reduced launch vehicle performance on the Block 1. Launch availability and orbital debris risk will be traded to find the best flight profile for both SLS and Orion. [View Full Paper]

[*] Aerospace Engineer, Guidance Navigation and Mission Design Branch, NASA, Marshall Space Flight Center, Huntsville, Alabama 35812, USA.
[†] Aerospace Engineer, Flight Mechanics and Trajectory Design Branch, NASA, Johnson Space Center, Houston, Texas 77058, USA.
[‡] Aerospace Engineer, XI4, Jacobs Technology, Johnson Space Center, Houston, Texas 77058, USA.
[§] Aerospace Engineer, XI411, NASA, Johnson Space Center, Houston, Texas 77058, USA.
[**] Aerospace Engineer, Flight Mechanics and Trajectory Design Branch, NASA, Johnson Space Center, Houston, Texas 77058, USA.
[††] Aerospace Engineer, Guidance Navigation and Mission Design Branch, Bevilacqua Research Corporation/Jacobs Space Exploration Group, Marshall Space Flight Center, Huntsville, Alabama 35812, USA.
[‡‡] Aerospace Engineer, Systems Analysis Branch, Jacobs Space Exploration Group, Marshall Space Flight Center, Huntsville, Alabama 35812, USA.
[§§] Aerospace Engineer, GV111, NASA, Johnson Space Center, Houston, Texas 77058, USA.
[***] GN&C Engineer, Guidance Navigation and Mission Design Branch, Troy7/Jacobs Space Exploration Group, Marshall Space Flight Center, Huntsville, Alabama 35812, USA.

FUEL-OPTIMAL CONVEX TRAJECTORY OPTIMIZATION OF RENDEZVOUS ON ELLIPTICAL ORBITS

Mauro Massari[*] and Paolo Massioni[†]

In this paper a new approach to constrained low-thrust trajectory optimization for rendezvous on elliptical orbits is presented. The approach is derived from a technique developed in the control engineering community, known as Sum Of Squares. Approximating the solution as a polynomial with respect to time, the constraints are reduced to bounds on polynomials. The polynomial bounding problem is then formulated as a convex optimization problem which does not require an initial guess for the solution. This approach is well suited for problems under linear dynamic equations, therefore perfectly fitting the case of spacecraft relative motion. [View Full Paper]

[*] Department of Aerospace Science and Technology, Politecnico di Milano, Via La Masa 34, 20156, Milan, Italy.
E-mail: mauro.massari@polimi.it.
[†] Laboratoire Ampère UMR CNRS 5005, INSA Lyon, Université de Lyon, Villeurbanne, France.
E-mail: paolo.massioni@insalyon.fr.

NEW HORIZONS 2014MU69 FLYBY DESIGN AND OPERATION

Yanping Guo* and Wayne R. Schlei†

After the Pluto flyby in July 2015, the New Horizons spacecraft continued its journey to the outermost region of solar system to explore the Kuiper Belt. New Horizons encountered a Kuiper Belt Object (KBO), designated 2014MU69, on January 1, 2019, for the closest ever observations of a KBO and made the farthest planetary flyby. The flyby design included a prime and an alternate flyby trajectory with the closest approach distances at 3,500 km and 10,000 km, respectively. Seven trajectory correction maneuvers (TCMs) were scheduled during the final approach phase (90 days prior to closest approach) for flight path refinement to achieve the B-plane target and time of closest approach of the desired MU69 flyby based on updated orbit prediction. Eventually, only three TCMs were performed, resulting in only a final offset of 36 km in the 2014MU69 B-plane and 19 seconds from the closest approach time. [View Full Paper]

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

† Senior Professional Staff, Space Exploration Sector, Johns Hopkins University Applied Physics Laboratory, 11100 Johns Hopkins Road, Laurel, Maryland 20723-6099, USA.

THE LOW-THRUST INTERPLANETARY EXPLORER: A MEDIUM-FIDELITY ALGORITHM FOR MULTI-GRAVITY ASSIST LOW-THRUST TRAJECTORY OPTIMIZATION

Martin T. Ozimek,[*] Jack F. Riley[*] and Juan Arrieta[†]

The Johns Hopkins University Applied Physics Laboratory and Nabla Zero Labs have developed a multi-gravity assist, low-thrust trajectory optimization software tool known as **LInX**—the *Low-thrust Interplanetary eXplorer*. It relies on generalized Sims-Flanagan transcription with forward and backward direct multiple shooting and nonlinear programming. The tool features fully analytic partial derivatives with accurate hardware models and is well-suited for medium-fidelity applications. There are many novel aspects to **LInX**, including a modular implementation based on the latest C++ standard; an efficient parallel implementation of **SPICE** for ephemerides interpolation; and support for deployment in heterogeneous computing environments for large-scale applications. Results against established trajectory optimization benchmark problems exhibit favorable convergence and performance characteristics. [View Full Paper]

[*] Mission Design Engineer, Space Exploration Sector, The Johns Hopkins Applied Physics Laboratory, 11101 Johns Hopkins Road, Laurel, Maryland 20723, USA. E-mail: Martin.Ozimek@jhuapl.edu, Jack.Riley@jhuapl.edu.
[†] CEO, Nabla Zero Labs, 177 East Colorado Blvd., Suite 2025, Pasadena, California 91105, USA. E-mail: Juan.Arrieta@nablazerolabs.com.

A TWO-LEVEL DIFFERENTIAL CORRECTIONS ALGORITHM FOR LOW-THRUST SPACECRAFT TRAJECTORY TARGETING

Collin E. York* and Kathleen C. Howell†

Applications of low-thrust propulsion to spaceflight in multi-body environments require a targeting algorithm to produce suitable trajectories on the ground and on board spacecraft. The two-level targeter with low thrust (TLT-LT) supplies a framework for implementation of differential corrections schemes in both autonomous spacecraft applications and the larger design space of pre-mission planning. Extending existing two-level corrections algorithms, applications of the TLT-LT to spacecraft with a range of propulsive capabilities, from nearly-impulsive to low-thrust, are explored. The process for evaluating partial derivatives is generalized, allowing for reduced logic complexity and increased flexibility in designing sequences of thrusting and ballistic segments. [View Full Paper]

* Ph.D. Student, School of Aeronautics and Astronautics, Purdue University, 701 W. Stadium Avenue, West Lafayette, Indiana 47907, USA. E-mail: york0@purdue.edu.
† Hsu Lo Distinguished Professor of Aeronautics and Astronautics, School of Aeronautics and Astronautics, Purdue University, 701 W. Stadium Avenue, West Lafayette, Indiana 47907, USA. E-mail: howell@purdue.edu.

AAS 19-389

SCIENCE ORBITS DESIGN FOR THE LUNAR CUBESAT EQUULEUS AND FOR THE PHOBOS SAMPLE RETURN MISSION MMX

Takuya Chikazawa,* Nicola Baresi,† Naoya Ozaki,‡ Stefano Campagnola§ and Yasuhiro Kawakatsu**

The candidate science orbits for two JAXA missions heading to three-body system, EQUULEUS and MMX, are presented in this paper. Both of these missions need to conduct science observations while coping with tight engineering constraints such as thermal and power budgets. Due to these requirements, eclipses may become a significant issue for both missions. To minimize or avoid eclipses, we introduce key design parameters for synodic resonant periodic orbits: the synodic ratio and the elongation angle between the Sun and the two primaries. By combining these parameters, we can obtain science orbits that avoid or minimize eclipses in a full ephemeris model. This approach is demonstrated for the science orbit design of both EQUULEUS and MMX. [View Full Paper]

* Graduate Student, Department of Advanced Energy, The University of Tokyo, 7-3-1 Hongo, Bunkyo-ku, Tokyo 113-8654, Japan.

† JAXA Aerospace Project Research Associate, Department of Space Flight Systems, ISAS/JAXA, 3-1-1 Yoshinodai, Chuo-ku, Sagamihara, Kanagawa 252-5210, Japan.

‡ Postdoctoral Fellow, Department of Space Flight Systems, ISAS/JAXA, 3-1-1 Yoshinodai, Chuo-ku, Sagamihara, Kanagawa 252-5210, Japan.

§ Mission Design Engineer, Jet Propulsion Laboratory, California Institute of Technology, 4800 Oak Grove Drive, Pasadena, California 91109, USA.

** Professor, Department of Space Flight Systems, ISAS/JAXA, 3-1-1 Yoshinodai, Chuo-ku, Sagamihara, Kanagawa 252-5210, Japan.

MULTI-OBJECTIVE OPTIMIZATION OF LOW THRUST TRAJECTORIES FOR PROPELLANT MASS, TIME OF FLIGHT, AND RADIATION DOSE

Christopher G. Lorenz,[*] Lake A. Singh[†] and Jose J. Guzman[‡]

Low thrust trajectories typically trade propellant usage and transfer time. Radiation dosage is traditionally minimized using transfer time as a surrogate, which may not fully capture the radiation exposure of the satellite. This paper treats radiation dose directly by adopting a multi-objective optimization approach with the inclusion of a radiation model to explore the trade-space of trajectory options for the objectives of minimum propellant usage, minimum transfer time, and minimum radiation dose. Results indicate that trajectories are available that offer decreased radiation dose at the expense of increased transfer time and/or increased propellant usage, providing flexibility for mission planners.

[View Full Paper]

[*] Member of the Technical Staff, Performance Modeling and Analysis Department, The Aerospace Corporation, 14745 Lee Road, Chantilly, Virginia 20151, USA.

[†] Systems Director, Future Architectures Department, The Aerospace Corporation, 14745 Lee Road, Chantilly, Virginia 20151, USA.

[‡] Engineering Manager, Performance Modeling and Analysis Department, The Aerospace Corporation, 14745 Lee Road, Chantilly, Virginia 20151, USA.

A RELAXATION APPROACH FOR HYBRID MULTI-OBJECTIVE OPTIMAL CONTROL: APPLICATION TO MULTIPLE DEBRIS REMOVAL MISSIONS

Lorenzo A. Ricciardi[*] and Massimiliano Vasile[†]

This paper presents a novel approach to the solution of multi-phase multi-objective hybrid optimal control problems. The proposed solution strategy extends previous work which integrated the Direct Finite Elements Transcription (DFET) method to transcribe dynamics and objectives, with a memetic strategy called Multi Agent Collaborative Search (MACS). The problem is reformulated as two non-linear programming problems: a bi-level and a single level one. In the bi-level formulation the outer level, handled by MACS, generates trial control vectors that are then passed to the inner level, which enforces the feasibility of the solution. Feasible control vectors are then returned to the outer level to evaluate the corresponding objective functions. The single level formulation is also run periodically to ensure local convergence to the Pareto front. In order to treat mixed integer problems, the heuristics of MACS have been modified in order to preserve the discrete nature of integer variables. For the single level refinement and the inner level of the bi-level approach, discrete variables are relaxed and treated as continuous. Once a solution to the relaxed problem has been found, a smooth constraint is added to systematically force the relaxed variables to assume integer values. The approach is first tested on a simple motorised travelling salesmen problem and then applied to the mission design of a multiple debris removal mission. [View Full Paper]

[*] Ph.D. Candidate, Aerospace Centre of Excellence, Mechanical & Aerospace Engineering, 75 Montrose Street, G1 1XJ, Glasgow, UK. AIAA Student Member.
[†] Professor, Aerospace Centre of Excellence, Mechanical & Aerospace Engineering, 75 Montrose Street, G1 1XJ, Glasgow, UK. AIAA Member.

LOW ENERGY ESCAPE USING TUBE DYNAMICS ASSOCIATED WITH QUASI-HALO ORBIT

Kazutoshi Takemura,* Nicola Baresi,† Yasuhiro Kawakatsu‡ and Hiroaki Yoshimura§

Analysis of tube dynamics under two dimensions has been analyzed by Koon et al.[2] However, analysis in three dimensions has not been done sufficiently. In this work, we discuss on designing Mars escape trajectory in the three-body system via invariant manifolds. In contrast with the conventional methods, we propose to use invariant manifolds from quasi-periodic invariant tori and investigate quasi-halo orbits and their associated tubes. Finally, we show how the invariant manifolds of quasi-periodic orbits can provide new escape trajectories from the Martian system in the circular restricted three-body problem. [View Full Paper]

* Graduate Student, Department of Applied Mechanics, Waseda University, 3-4-1 Okubo, Shinjuku-ku, Tokyo 169-8555, Japan.
† JAXA Project Research Associate, ISAS/JAXA, 3-1-1 Yoshinodai, Chuo-ku, Sagamihara, Kanagawa 252-5210, Japan.
‡ Professor, ISAS/JAXA, 3-1-1 Yoshinodai, Chuo-ku, Sagamihara, Kanagawa 252-5210, Japan.
§ Professor, Department of Applied Mechanics and Aerospace Engineering, Waseda University, 3-4-1 Okubo, Shinjuku-ku, Tokyo 169-8555, Japan.

QUASI-SATELLITE ORBIT TRANSFERS VIA MULTI-REVOLUTIONAL PERIODIC ORBITS

Kento Ichinomiya,[*] Nicola Baresi,[†] Yasuhiro Kawakatsu[‡] and Tomohiro Yanao[§]

This paper explores the application of multi-revolutional periodic orbits to transfer between single-revolutional quasi-satellite orbits around the Martian moon Phobos. Multi-revolutional periodic orbits are retrograde trajectories that repeat after multiple revolutions around Phobos. At first, we generate them by conventional predictor-corrector scheme and bifurcation analysis and find many candidate options for trajectory design analyses. Next, we explore transfer solutions between different single-revolutional periodic quasi-satellite orbits. We find that, if we choose appropriate multi-revolutional periodic orbits, we can reduce the transfer time and ΔV, as well as increase the robustness of the transfers from a contingency analysis standpoint. [View Full Paper]

[*] Graduate Student, Department of Applied Mechanics, Waseda University, Shinjuku, Tokyo, 169-8555, Japan.
[†] Aerospace Project Research Associate, Japan Aerospace Exploration Agency, Sagamihara, Kanagawa, 252-5210, Japan.
[‡] Professor, Department of Space Flight Systems, Japan Aerospace Exploration Agency, Sagamihara, Kanagawa, 252-5210, Japan.
[§] Professor, Department of Applied Mechanics, Waseda University, Shinjuku, Tokyo, 169-8555, Japan.

AAS 19-424

INTEGRATED OPTIMIZATION OF ASCENT TRAJECTORY AND SRM DESIGN OF MULTISTAGE LAUNCH VEHICLES

Lorenzo Federici,* Alessandro Zavoli,† Guido Colasurdo,‡
Lucandrea Mancini§ and Agostino Neri**

This paper presents a methodology for the concurrent first-stage preliminary design and ascent trajectory optimization, with application to a Vega-derived Light Launch Vehicle. The reuse as first stage of an existing upper-stage (Zefiro 40) requires a propellant grain geometry redesign, in order to account for the mutated operating conditions. An optimization code based on the parallel running of several Differential Evolution algorithms is used to find the optimal internal pressure law during Z40 operation, together with the optimal thrust direction and other relevant flight parameters of the entire ascent trajectory. Payload injected into a target orbit is maximized, while respecting multiple design constraints, either involving the alone solid rocket motor or dependent on the actual flight trajectory. Numerical results for SSO injection are presented. [View Full Paper]

* PhD Student, Department of Mechanical and Aerospace Engineering, Sapienza University of Rome, Rome, Italy.
† Research Assistant, Department of Mechanical and Aerospace Engineering, Sapienza University of Rome, Rome, Italy.
‡ Full Professor, Department of Mechanical and Aerospace Engineering, Sapienza University of Rome, Rome, Italy.
§ Master Student in Space Transportation Systems, Sapienza University of Rome, Rome, Italy.
** Head of VEGA-C Launcher System Integration and Launch System Synthesis Office, ESA ESRIN - VEGA Integrated Project Team, Frascati (Rome), Italy.

AAS 19-442

USING THE PARAMAT SYSTEM IN MISSION ANALYSIS AND DESIGN

Darrel J. Conway[*] and Darren D. Garber[†]

Thinking Systems is building a general purpose parallel processing mission analysis tool, Paramat, for large scale analysis problems and for a new class of dynamic mission analysis problems. The new analysis features stem from the introduction of small launch vehicles, and from improved electric propulsion systems and rideshare opportunities. Paramat, an extension of GMAT, runs GMAT's core numerical engine into a parallel processing environment. Paramat has been used previously for Monte-Carlo analysis studies. Recent additions to the tool enable launch window analysis and parametric scans to seek and find useful trajectories. Current development tasks include enhancements to facilitate trajectory optimization.

In this paper, the combination of Paramat and GMAT is used to demonstrate three new trajectory design tasks. Each of these missions is currently under consideration and tasked to NXTRAC and Thinking Systems to assess the feasibility and utility of each proposed trajectory. The first is a transfer from low Earth orbit to the Moon; the second, a deep space trajectory from an asteroid-bound rideshare to an orbital capture at Venus. The final example is the design of a rideshare and ensuing Earth flyby trajectory that raises the spacecraft out of the ecliptic plane. The work flow used for these mission designs is described for each example, starting from initial concept, through early examination of the problem, and into exploration of design options.

The lunar transfer problem examines the feasibility of designing the trajectory of a low mass spacecraft launched from a commercially available small launch vehicle and thruster. The spacecraft performs a flyby of the Moon with the purpose of imaging the far side and returning the images to Earth. The transfer is modeled starting from a parking orbit achievable using a small launch vehicle. The payload is a small spacecraft that uses a solid upper stage for the transfer orbit insertion. Paramat is used to scan through potential transfer insertions from the initial orbit, searching for a suitable transfer to generate the desired lunar flyby trajectory.

The Venus transfer starts from a piggyback ride on the launch vehicle for the Lucy mission. The insertion state obtained from this ride is used to seed the Venus transfer trajectory. Paramat is used to scan through options for a small correction maneuver that tunes an Earth flyby, locating a close approach to Venus on a subsequent orbit. Once the close approach has been found, an insertion maneuver is performed to place the spacecraft into orbit.

The final example uses the same Lucy piggyback state, followed by a tuning maneuver, to perform an Earth flyby that raises a spacecraft's trajectory out of the ecliptic plane. The goal of the mission is to reach a height of fifty million kilometers above the ecliptic in order to study the density and distribution of interplanetary dust responsible for the zodiacal light.

The combination of GMAT and Paramat results in a set of tools that enable mission planning like the cases presented here. Lessons learned from these design exercises are used to update Paramat as it nears public availability. [View Full Paper]

[*] Senior Scientist and CEO, Thinking Systems, Inc., 437 W Thurber Road, Suite 6, Tucson, Arizona 85718, USA.
[†] President, NXTRAC, 800 S PCH Suite 8-247, Redondo Beach, California 90277, USA.

SERIES SOLUTION FOR MOTION IN AN ARBITRARY POTENTIAL FIELD*

Nathan Strange†

In this paper, the equations of motion for a test particle in an arbitrary potential field is solved as a formal power series. This solution is in terms of the time derivatives of the motion of the test particle. These derivative may be used to construct a Taylor series for the motion of the particle in the vicinity of given initial conditions. [View Full Paper]

† Jet Propulsion Laboratory / California Institute of Technology, 4800 Oak Grove Drive, Pasadena, California 91109-8099, USA.

AAS 19-448

Q-LAW AIDED DIRECT TRAJECTORY OPTIMIZATION FOR THE HIGH-FIDELITY, MANY-REVOLUTION LOW-THRUST ORBIT TRANSFER PROBLEM

Jackson L. Shannon,[*] Martin T. Ozimek,[†]
Justin A. Atchison[†] and Christine M. Hartzell[‡]

Low-thrust spacecraft trajectory optimization for the many-revolution orbital transfer problem is especially challenging due to the dimension of the problem and the fact that perturbation accelerations prevent or complicate accurate analytical solutions. This analysis seeks to simplify the calculation of the non-averaged, high-fidelity spiral trajectory through the use of the well-known Q-Law Guidance. Here, Q-Law is used to seed various phases of the direct trajectory optimization problem. We demonstrate the trade space between the fast calculation speed of Q-Law and the time or mass optimality of the full optimization problem using the common example of a GTO to GEO transfer. We find that a computationally efficient, near-optimal solution can be achieved using an approach that combines features of Q-Law and direct optimization. Q-Law is used for the first half of a spiral trajectory and direct optimization is used for the second half. This reduces the direct optimization problem to a lower dimension and enables the spacecraft to reach a specific final state. Q-Law is particularly effective for portions of the trajectory where there are many eclipses, which can challenge direct optimization software. [View Full Paper]

[*] Ph.D. Student, Department of Aerospace Engineering, University of Maryland-College Park, College Park, Maryland 20740, USA.
[†] Mission Design Engineer, Space Exploration Sector, Johns Hopkins Applied Physics Laboratory, 11101 Johns Hopkins Road, Laurel, Maryland 20723, USA.
[‡] Assistant Professor, Department of Aerospace Engineering, University of Maryland-College Park, College Park, Maryland 20740, USA.

AAS 19-449

VISUAL INTERACTIVE TRAJECTORY DESIGN

Ravishankar Mathur*

A method of altering trajectories via visual "grab-and-drag" gestures with immediate graphical response, called Visual Interactive Trajectory Design (VITD), is presented. The various components of VITD are defined (e.g. draggable objects), and how they affect the trajectory is discussed. An implementation of VITD is demonstrated that uses the General Mission Analysis Tool (GMAT) to propagate trajectories, and visualizes them in realtime using the OpenFrames 3D visualization API. Examples of using VITD are shown, including finding a lunar free-return trajectory by visually rotating the trajectory's initial velocity vector. The benefits of VITD are explored, including for teaching, exploring the design space, and generating initial-guess trajectories for optimization. [View Full Paper]

* Sr. GN&C Engineer, Emergent Space Technologies Inc., Laurel, Maryland 20707, USA. AIAA Member.

ON-ORBIT SERVICING MISSION DESIGN IN A DYNAMIC CLIENT ENVIRONMENT[*]

Jennifer S. Hudson[†] and Daniel Kolosa[‡]

Mission design for a versatile, robotic servicing spacecraft can be formulated as a combinatorial-optimization problem. If a servicing spacecraft operates in a dynamic environment, where new client spacecraft with urgent servicing needs emerge at different times, then decisions about operational sequencing and client-to-client transfer trajectories will play a significant role in overall mission success and profitability. This problem is investigated using stochastic methods. A model for future client demand is proposed and Monte Carlo simulations are used to evaluate likely mission scenarios. High-thrust and low-thrust cases are considered. A low-thrust trajectory optimization method is used to assess transfer time and propellant requirements for high-value mission scenarios. Results provide insights into the expected frequency and ordering of various robotic operations (inspection, repair, refueling, repositioning, and retirement) in future servicing missions. [View Full Paper]

[*] Approved for Public Release, Distribution Unlimited.

[†] Associate Professor, Department of Mechanical and Aerospace Engineering, Western Michigan University, 4601 Campus Drive, Kalamazoo, Michigan 49009-5343, USA.

[‡] PhD Candidate, Department of Mechanical and Aerospace Engineering, Western Michigan University, 4601 Campus Drive, Kalamazoo, Michigan 49009-5343, USA.

AAS 19-461

DYNAMIC OPTIMIZATION FOR LARGE SCALE ACTIVE DEBRIS REMOVAL MISSION DESIGN APPLICATIONS

Tyler Doogan,[*] Manoranjan Majji[†] and Terry Alfriend[‡]

A three stage approach for active debris removal mission analysis is presented in this paper. The first stage of the planning process entails the use of clustering algorithms to partition a large catalogue of orbits into groups of user defined sizes. It is shown that this operation is tantamount to histogram analysis in non-Euclidean spaces. The second stage of the approach then solves a dynamic traveling salesman problem to compute a visitation through each cluster. The final stage optimizes the departure times for each intra-cluster transfer. The optimal order of visitation is then used as a large scale (decadal scale) preliminary debris removal mission plan. [View Full Paper]

[*] Graduate Research Assistant, Land, Air and Space Robotics (LASR) Laboratory, Aerospace Engineering, Texas A& M University, College Station, Texas 77843-3141, USA.
[†] Assistant Professor, Director, Land, Air and Space Robotics (LASR) Laboratory, Aerospace Engineering, Texas A& M University, College Station, Texas 77843-3141, USA.
[‡] University Distinguished Professor, Aerospace Engineering, Texas A& M University, College Station, Texas 77843-3141, USA.

AAS 19-464

MODELING ATTITUDE-DEPENDENT MANEUVER ERRORS WITH POLYNOMIAL CHAOS EXPANSIONS

Brandon A. Jones*

This paper presents a framework for including random inputs on the unit sphere in Polynomial Chaos Expansions (PCEs) to decouple attitude dependent execution errors from magnitude errors. To maintain efficiency in the expansion, the basis functions must be orthogonal with respect to the density function of the inputs. Due to the unit norm constraint, random directions in three-dimensional space are defined on the unit sphere, which requires an extension to existing PCE methods. This paper presents the mathematical framework and revisits a previous test case in the literature that leveraged directional quantities. [View Full Paper]

* Assistant Professor, Department of Aerospace Engineering and Engineering Mechanics, The University of Texas at Austin, Austin, Texas, 78712-1221, USA. E-mail: brandon.jones@utexas.edu.

DISPOSAL, DEPLOYMENT, AND DEBRIS IN NEAR RECTILINEAR HALO ORBITS

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

A proposed Gateway facility in a lunar Near Rectilinear Halo Orbit (NRHO) will serve as an outpost in deep space, with spacecraft periodically arriving and departing. Departing objects will include logistics modules, requiring safe disposal; cubesats, deployed to various destinations; and debris objects, whose precise paths may be unknown. Escape dynamics from NRHOs are complex; motion is primarily influenced by the Earth and Moon within the orbit, but spacecraft are significantly impacted by solar gravity upon departure. The current investigation explores the dynamics of departure from the NRHO, including the risk of debris recontact, safe heliocentric disposal, and deployment to select destinations. [View Full Paper]

[*] Principal Systems Engineer, a.i. solutions, Inc., 2224 Bay Area Blvd., Houston, Texas 77058, USA. E-mail: diane.davis@ai-solutions.com.

[†] Graduate Student, School of Aeronautics and Astronautics, Purdue University, Armstrong Hall of Engineering, 701 W. Stadium Ave., West Lafayette, Indiana 47907-2045, USA. E-mail: kboudad@purdue.edu.

[‡] Principal Software Engineer, a.i. solutions, Inc., 4500 Forbes Blvd., Lanham, Maryland 20706, USA. E-mail: sean.phillips@ai-solutions.com.

[§] Hsu Lo Distinguished Professor, School of Aeronautics and Astronautics, Purdue University, Armstrong Hall of Engineering, 701 W. Stadium Ave., West Lafayette, Indiana 47907-2045, USA. E-mail: howell@purdue.edu. Fellow AAS; Fellow AIAA.

ROBUST TRAJECTORY DESIGN FOR ASTEROID ORBITERS

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

In low gravity environments with large uncertainties, a robust orbit transfer may be preferred over a fuel-optimal transfer. Such a case exists in the orbital environment around small asteroids, where transfers can be achieved with maneuvers of relatively small magnitudes. However, these trajectories are also highly sensitive to maneuver execution errors and state uncertainties. This paper will investigate a parametric robust optimization method with applications to asteroid missions, where the robust-optimal solution will be the trajectory that minimizes the variance of error in a terminal constraint under state and control uncertainties. The proposed method requires analytically mapping state and control errors to a terminal constraint. A single-phase mapping solution will be developed for application to fully open-loop trajectories. Additionally, a multiple-phase mapping solution will be proposed for trajectories in which maneuvers are redesigned to correct state errors throughout the trajectory. Robust trajectories will be designed for three cases: orbit corrections about a small asteroid using the Clohessy-Wiltshire equations, orbit transfers in the two-body problem, and a heliocentric asteroid approach trajectory approximated with rectilinear motion. [View Full Paper]

[*] PhD Student, Aerospace Engineering Sciences, 429 UCB, University of Colorado Boulder, Colorado 80309, USA.

[†] Distinguished Professor, Aerospace Engineering Sciences, 429 UCB, University of Colorado Boulder, Colorado 80309, USA.

EFFICIENT COMPUTATION OF OPTIMAL LOW THRUST GRAVITY PERTURBED ORBIT TRANSFERS

Robyn Woollands,[*†] Ehsan Taheri[‡] and John L. Junkins[§]

We have developed a new method for solving low-thrust fuel-optimal orbit transfer problems in the vicinity of a large body (planet or asteroid), considering a high-fidelity spherical harmonic gravity model. The algorithm is formulated via the indirect optimization method, leading to a two-point boundary value problem (TPBVP). We make use of a hyperbolic tangent smoothing law for performing continuation on the thrust magnitude to reduce the sharpness of the control switches in early iterations and thus promote convergence. The TPBVP is solved using the method of particular solutions (MPS) shooting method and Picard-Chebyshev numerical integration. Application of Picard-Chebyshev integration affords an avenue for increased efficiency that is not available with step-by-step integrators. We demonstrate that computing the particular solutions with only a low-fidelity force model greatly increases the efficiency of the algorithm while ultimately achieving near machine precision accuracy. A salient feature of the MPS is that it is parallelizable, and thus further speedups are available. It is also shown that, for near-Earth orbits and over a small number of en-route revolutions around the Earth, only the zonal perturbation terms are required in the costate equations to obtain a solution that is accurate to machine precision and optimal to engineering precision. The proposed framework can be used for trajectory design around small asteroids and also for orbit debris rendezvous and removal tasks. [View Full Paper]

[*] Mission Design Engineer, Jet Propulsion Laboratory, California Institute of Technology, Pasadena, California 91109, USA.
[†] Adjunct Assistant Professor, Department of Aerospace Engineering, Texas A&M University, College Station, Texas 77843-3141, USA. Member AAS.
[‡] Research Assistant Professor, Department of Aerospace Engineering, Texas A&M University, College Station, Texas 77843-3141, USA. Member AAS.
[§] Distinguished Professor, Department of Aerospace Engineering, Texas A&M University, College Station, Texas 77843-3141, USA. Fellow AAS.

AAS 19-496

HYPERBOLIC-TANGENT-BASED SMOOTHING WITH STATE TRANSITION MATRIX IMPLEMENTATION FOR GENERATING FUEL-OPTIMAL TRAJECTORIES

Vishala Arya,[*] Ehsan Taheri[†] and John L. Junkins[‡]

Indirect optimization methods hold a special place among the techniques used for solving optimal control problems since they guarantee local optimality of the resulting solutions. On the other hand, complications occur during numerical calculations when optimal control has bang-bang or bang-off-bang structure. Traditionally, smoothing techniques such as quadratic, logarithmic and extended logarithmic have been employed with homotopic or numerical continuation method to overcome numerical difficulties. In this paper, a recently introduced hyperbolic tangent smoothing is used for solving the two-point boundary-value problem associated with time-fixed, rendezvous-type, fuel-optimal maneuvers. The equations of motion are expressed in terms of the Cartesian coordinates. Implementation of the State Transition Matrix (STM) along with the hyperbolic tangent smoothing is demonstrated that enhances convergence performance of solvers that use iterative Newton update schemes. Utility of the proposed construct is demonstrated through solving a number of low-thrust fuel-optimal trajectories. [View Full Paper]

[*] MSc Student, Department of Aerospace Engineering, Texas A&M University, College Station, Texas 77843-3141, USA. AIAA Member.

[†] Research Assistant Professor, Department of Aerospace Engineering, Texas A&M University, College Station, Texas 77843-3141, USA. AIAA Member.

[‡] Distinguished Professor, Department of Aerospace Engineering, Texas A&M University, College Station, Texas 77843-3141, USA. Honorary Fellow AIAA.

AAS 19-504

VECTOR FORMULATIONS FOR SPHERICALLY BOUNDED SEARCH SPACES

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

In the optimization of spacecraft trajectories, it is often the case that there is some naturally arising bound(s) on the magnitudes of the associated velocities. Such constraints lead to a spherical or, more generally, an elliptical search space. Unfortunately, typical problem transcriptions instead search within a Cartesian box, applying these bounds to each dimension independently. This leads to a search space where nearly half of the search space is known to be useless a priori. The present work investigates an alternate interpretation of a velocity decision vector and assesses the effects of precluding this known sub-optimal space. [View Full Paper]

* Ph.D. Student in Mechanical Engineering, University of Vermont, Burlington, Vermont 05405, USA.
† Professor of Mechanical Engineering, University of Vermont, Burlington, Vermont 05405, USA.

MULTI-OBJECTIVE OPTIMIZATION FOR SPACECRAFT DETECTION AVOIDANCE USING REACHABILITY SETS

Jason A. Reiter,[*] Zachary J. Hall,[†] David B. Spencer[‡] and Puneet Singla[§]

The Conjugate Unscented Transform allows for an easy calculation of reachability sets with a minimal number of full model propagations. The computation time savings that come with this method encourages implementation of reachability sets in more complex problems. Spacecraft maneuver planning for detection avoidance is unique in that all objectives may not be met by moving some minimum distance from the nominal orbit. Analyzing the reachable sets in topographic coordinates instead presents a unique metric for quantifying detection avoidance. Combining ground-track manipulation and propellant-use in reachability-based multi-objective optimization gives planners an efficient and accurate method for designing detection avoidance maneuvers. [View Full Paper]

[*] Graduate Student, Department of Aerospace Engineering, 229 Hammond Building, The Pennsylvania State University, University Park, Pennsylvania 16802, USA.

[†] Graduate Student, Department of Aerospace Engineering, 229 Hammond Building, The Pennsylvania State University, University Park, Pennsylvania 16802, USA.

[‡] Professor, Department of Aerospace Engineering, 229 Hammond Building, The Pennsylvania State University, University Park, Pennsylvania 16802, USA.

[§] Associate Professor, Department of Aerospace Engineering, 229 Hammond Building, The Pennsylvania State University, University Park, Pennsylvania 16802, USA.

ANALYSIS OF ANALOG-TO-DIGITAL CONVERSION TECHNIQUES FOR SATELLITE ORBITAL MANEUVERING USING COLD GAS THRUSTERS

Spencer Harwood* and Marco Ciarcià†

In this work, analog-to-digital conversion strategies for cold gas thrust actuation are examined. In particular, the interest is directed toward the accurate and efficient actuation of continuous thrust histories via on-off thrusting action. The strategies studied in this work are pulse-width modulation, delta-sigma modulation, and a novel compensated pulse-width modulation. The scenario of interest involves an orbiting small satellite performing proximity maneuvers propelled by a single cold gas thruster. Different settings for the actuation strategies are studied to determine their effects on accuracy and efficiency in propellant usage. The results are confirming the advantages of delta-sigma modulation over pulse-width modulation in terms of actuation accuracy. Nevertheless, the former might become inaccurate if not properly tuned. On the other hand, the compensated pulse-width modulation shows excellent tracking performance for a wide range of inner settings. In terms of propellant use, the delta-sigma modulation performs marginally better over the other two strategies. [View Full Paper]

* Graduate Research Assistant, Department of Mechanical Engineering, Crothers Engineering Hall, South Dakota State University, Brookings, South Dakota 57007, USA.

† Assistant Professor, Department of Mechanical Engineering, Crothers Engineering Hall 210, South Dakota State University, Brookings, South Dakota 57007, USA.

MULTI-OBJECTIVE OPTIMIZATION OF SPACECRAFT TRAJECTORIES FOR SMALL-BODY COVERAGE MISSIONS WITH NON-KEPLERIAN ORBITAL DYNAMICS

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

Visual coverage of surface elements of a small celestial body requires multiple images to be taken that must satisfy numerous requirements on their viewing angles, illumination angles, times of day, and combinations thereof. Finding trajectories that allow for these conditions to be met in a timely manner is a nontrivial task and is made more difficult by the competing criteria for such trajectories. This work phrases the search for suitable trajectories as an optimization problem handled with a multi-objective evolutionary algorithm. [View Full Paper]

* Mechanical Engineering Graduate Student, University of Vermont, Burlington, Vermont 05405, USA.
† Mechanical Engineering Graduate Student, University of Vermont, Burlington, Vermont 05405, USA.
‡ Professor of Mechanical Engineering, University of Vermont, Burlington, Vermont 05405, USA.

INNOVATIVE SOLAR SAIL EARTH-TRAILING TRAJECTORIES ENABLING SUSTAINABLE HELIOPHYSICS MISSIONS

James B. Pezent,[*] Andrew Heaton[†] and Rohan Sood[‡]

The presented trajectory design study demonstrates that near-future solar sails can reach and maintain innovative science orbits about non-traditional Earth-trailing equilibrium points. The proposed configurations can enable long duration stereoscopic solar imaging while potentially alleviating telemetry requirements constraining current solar sail studies. Initial guesses for controlled periodic orbits about Earth-trailing (1.5°–15°) equilibrium points are constructed from a linearized solar sail circular restricted three body problem equations of motion. Orbits are then converged in the full nonlinear model using a high order direct collocation method. Transfers to Earth-trailing orbits are then constructed under the assumption that the solar sail is a secondary payload on a larger spacecraft en-route to the Sun-Earth L_1 Lagrange point. Naturally occurring gravitational manifolds flowing towards the Lagrange point, as well as navigation data from previous Lagrange point missions, are used to generate a set of baseline trajectories for the primary spacecraft. End-to-end trajectory design and optimization is then carried out to construct time optimal solar sail transfers to each target science orbit from initial conditions constrained to lie on the carrier spacecraft's Lagrange point trajectory. Additionally, trade studies are performed to assess how sail performance and Earth-trailing orbit selection affect transfer time of flight and instrument pointing accuracy. Results indicate that, based on current technological developments, near future solar sails are capable of station keeping about periodic Earth-trailing orbits while maintaining near-constant solar observation. Moreover, time of flights on the order of 1 year are observed for most combinations of sail performance and feasible initial conditions. [View Full Paper]

[*] Undergraduate Researcher, Astrodynamics and Space Research Laboratory, The University of Alabama, 245 7th Ave., Tuscaloosa, Alabama 35401, USA. E-mail: jbpezent@crimson.ua.edu.

[†] Senior Aerospace Engineer, EV/42, NASA Marshall Space Flight Center, NASA Marshall Space Flight Center, Huntsville, Alabama 35812, USA. E-mail: andrew.f.heaton@nasa.gov.

[‡] Assistant Professor, Astrodynamics and Space Research Laboratory, The University of Alabama, 245 7th Ave., Tuscaloosa, Alabama 35401, USA. E-mail: rsood@eng.ua.edu.

AAS 19-567

OBJECTIVE FUNCTION WEIGHT SELECTION FOR SEQUENTIAL LOW-THRUST ORBIT-RAISING OPTIMIZATION PROBLEM

Atri Dutta[*] and Lakshay Arora[†]

In this paper, we consider the low-thrust orbit-raising problem formulated as a sequence of optimal control sub-problems. This formulation is helpful in rapid and robust generation of geocentric electric orbit-raising trajectories, however this advantage comes at the cost of sub-optimality of the computed solutions. The objective function that is minimized in each optimal control sub-problem is a convex combination of components and reflects the deviation of the maneuvering spacecraft from the geosynchronous equatorial orbit. This paper explores the impact of weights the objective function components on the optimality gap of computed orbit-raising trajectories, and numerical examples based on a variety of orbit-raising scenarios are used to illustrate this effect. [View Full Paper]

[*] Assistant Professor, Aerospace Engineering, Wichita State University, 1845 Fairmount St Box 42, Wichita, Kansas 67260, USA.

[†] M.S. Student, Aerospace Engineering, Wichita State University, 1845 Fairmount St Box 42, Wichita, Kansas 67260, USA.

AAS 19-568

SYNTHESIS OF FUEL-OPTIMAL POWERED DESCENT TRAJECTORIES FOR PLANETARY LANDING MISSIONS

Minji Jo* and Dilmurat Azimov†

Synthesis of feasible and extremal planetary entry, descent and landing trajectories is investigated for a central Newtonian field. In this synthesis, all trajectories are started with the initial thrust arc and ended with the final thrust arc, and the ballistic arc connects both thrust arcs. The proposed synthesis is presented for feasible, extremal and fuel-optimal trajectories. The feasible trajectories are designed with the 7-state model and the extremal trajectories are considered with the 14-state model. The proposed synthesis can be used in mission design for planetary landing missions to the moon and Mars and for the sample return missions. [View Full Paper]

* Graduate Student, Mechanical Engineering Department, The University of Hawai'i at Manoa, 2540 Dole Street, Holmes 306, Honolulu, Hawai'i 96822, USA.

† Associate Professor, Mechanical Engineering Department, The University of Hawai'i at Manoa, 2540 Dole Street, Holmes 202A, Honolulu, Hawai'i 96822, USA.

ORBITAL DYNAMICS, PERTURBATIONS, AND STABILITY

Session Chairs:

Session 2: Richard Linares, Massachusetts Institute of Technology

Session 10: Thomas Kelecy, L3 - Applied Defense Solutions

STABILITY AND TARGETING IN DAWN'S FINAL ORBIT*

Daniel Grebow,† Nicholas Bradley‡ and Brian Kennedy‡

The Dawn spacecraft conducted two extended missions at Ceres following the completion of the primary mission in June 2016. The final orbit of the second extended mission was designed to have a 35-km periapsis altitude for 10x higher-resolution science. The mission ended in this orbit when the spacecraft ran out of attitude control propellant. In this paper, we describe the final orbit and discuss the challenges of flying this low at Ceres. We also include our stability analysis showing the spacecraft will remain in orbit for more than 20 years, as stipulated by the planetary protection requirements.

[View Full Paper]

† Outer Planet Mission Analysis Group, Mission Design and Navigation Section, Jet Propulsion Laboratory, California Institute of Technology. 4800 Oak Grove Drive, Pasadena, California 91109, USA.

‡ Outer Planet Navigation Group, Mission Design and Navigation Section, Jet Propulsion Laboratory, California Institute of Technology. 4800 Oak Grove Drive, Pasadena, California 91109, USA.

AAS 19-270

DESIGN AND CONTROL OF REPEAT GROUND TRACK ORBITS IN HIGH FIDELITY DYNAMICAL MODEL VIA HIGH ORDER POINCARÉ MAPPING

Roberto Armellin,[*] Yanchao He[†] and Ming Xu[‡]

A semi-analytical technique for both the design and control of repeat ground-track (RGT) orbits in a high fidelity dynamical model, including non-conservative forces and accurate Earth orientation parameters, is introduced. The method is based on the use of high-order expansion of Poincaré maps to propagate forward in time regions of the phase space for one, or more, repeat cycles. This map provides the means to efficiently study the effect that an impulse, applied at the Poincaré section crossing, produces on the ground-track pattern, thus enabling highly accurate design and control. The approach is applied to the design and control of missions like TerraSAR-X, Landsat-8, SPOT-7, IRS-P6, and UoSAT-12. [View Full Paper]

[*] Senior Lecturer, Surrey Space Centre, University of Surrey, Guildford, England GU2 7XH, United Kingdom.
[†] Engineer, Orbit Design Group, DFH Satellite Co., Ltd., 100094 Beijing, People's Republic of China.
[‡] Associate Professor, School of Astronautics, Beihang University, 100191 Beijing, People's Republic of China.

CAPTURE AN ASTEROID TO EARTH-MOON TRIANGULAR LIBRATION POINTS

Yuying Liang,[*] Jinjun Shan,[†] Ming Xu[‡] and Shijie Xu[§]

This paper is devoted to the capture mechanism of asteroids to the Earth-Moon system via triangular libration points. The dynamical problem is simplified as a combination of circular restricted three body problem (CR3BP) of the Earth and the Moon inside the Earth's sphere of influence (SOI) and a CR3BP of the Sun and the Earth. Due to the strong stability of motion near triangular libration points in the Earth-Moon system, the transfer segments inside the Earth's SOI is constructed by chaos-assisted method. The outside segment is then obtained by Lambert transfers and differential correction. To guide the selection of the target asteroid, the total fuel consumption is evaluated and illustrated ergodically on the plane of the semi-major axis and eccentricity of the asteroid's orbit in two extreme cases, i.e., perigee and apogee cases. Finally, the asteroids, whose orbits intersect directly with the Earth's SOI, are analyzed separately. [View Full Paper]

Post-Doctoral Fellowship, Department of Earth and Space Science and Engineering, York University, M3J 1P3, Canada. E-mail: linda024@yorku.ca.
[†] Professor, Department of Earth and Space Science and Engineering, York University, M3J 1P3, Canada. E-mail: jjshan@yorku.ca.
[‡] Associate Professor, School of Astronautics, Beihang University, 100191, China. E-mail: xuming@buaa.edu.cn.
[§] Professor, School of Astronautics, Beihang University, 100191, China. E-mail: starsjxu@163.com.

DROMO PROPAGATOR FOR HIGHLY PERTURBED PROBLEMS

Virginia Raposo-Pulido,* Hodei Urrutxua† and Jesús Peláez‡

DROMO is an orbital propagator developed in 2000 by the Space Dynamics Group at the Technical University of Madrid.[1] This special perturbation method is characterized by eight ODE's. A new extension of DROMO for strongly perturbed environments (DROMO-SPE) has been developed by introducing a new set of variables. Likewise, the DROMO formulation for elliptic orbits (ElliDROMO)[2,3] has been adapted for strongly perturbed environments (ElliDROMO-SPE). Both propagators are compared with the schemes proposed by Cowell, Kustaanheimo-Stiefel,[4] Sperling-Bürdet, and Palacios[5] as well as the classic versions of DROMO[6] in double and quadruple precision. Two different scenarios, where the perturbation plays an important role, are analyzed to assess the robustness of the new formulation: 1) the Tsien problem, and 2) artificial satellite orbiting Pluto. The results confirm the stability and reliability of the new formulation when the perturbation is close to unity. [View Full Paper]

* PhD 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.
† Assistant Professor, European Institute for Aviation Training and Accreditation, Rey Juan Carlos University, Camino del Molino s/n., 28943, Fuenlabrada - Madrid, Spain.
‡ Professor, Space Dynamics Group (SDG), E.T.S.I. Aeronáutica y del Espacio, Technical University of Madrid, Pza. Cardenal Cisneros, 3, E-28040, Madrid, Spain.

DEDICATED MISSION TO THE SUN-EARTH SADDLE POINT: A FEASIBILITY ASSESSMENT

Carmine Giordano,[*] Christian Trenkel[†] and Francesco Topputo[‡]

Gravitational Saddle Points are points in space where the net gravitational acceleration of solar system bodies cancels. Certain gravitational theories, motivated by the still unresolved Dark Matter problem, predict potentially verifiable deviations from General Relativity around these points. A dedicated mission to one of these points may be an attractive proposition, if feasible. In this paper, a scientific test case is built to set the requirements for that mission, then periodic orbits through the Sun–Earth Saddle Point, necessary to collect relevant data, are sought. The periodic orbits survey is made using a systematic approach, firstly addressing it in the circular restricted three-body problem with the Sun and the Earth as main bodies: first attempt trajectories are sought through a grid search and then refined using a simple shooting, differential correction scheme. Stability is evaluated and a classification is made. Restricted four body problem adding the Moon is used as middle complexity model in order to find quasi-periodic orbits. These are refined in a full ephemeris high-fidelity n-body model. Results show different solutions with diverse characteristics and properties. [View Full Paper]

[*] Ph.D. Student, Department of Aerospace Science and Technology, Politecnico di Milano, 20156 Milan, Italy.
[†] Airbus Defense and Space, UK.
[‡] Assistant Professor, Department of Aerospace Science and Technology, Politecnico di Milano, 20156 Milan, Italy.

AAS 19-328

SENSITIVITY ANALYSIS OF REGULARIZED ORBIT FORMULATIONS WITH INTERVAL ARITHMETIC

Hodei Urrutxua,[*]
European Institute for Aviation Training and Accreditation, Universidad Rey Juan Carlos
Space Dynamics Group, Technical University of Madrid

Youssef Souied[†] and Jesús Peláez[‡]
Space Dynamics Group, Technical University of Madrid

Regularized formulations provide a highly accurate description of the orbit as a geometric element, while the dynamical instabilities concentrate in the integration of the physical time. However, in highly perturbed problems, the geometric variables may also exhibit an important accumulation of propagation errors, where different formulations display distinctive error build-up patterns. To understand the error growth in each of the variables, in this paper interval arithmetic is used to perform a sensitivity analysis of the propagation error for various orbital formulations. The study considers a variety of orbital scenarios and conclusions are drawn based on the performed numerical tests. [View Full Paper]

[*] Assistant Professor at Universidad Rey Juan Carlos, Madrid, Camino del Molino S/N, 28942 Fuenlabrada, Spain.
[†] PhD Candidate, Technical University of Madrid, Pz. Cardenal Cisneros 3, 28040 Madrid, Spain.
[‡] Full Professor, at the Technical University of Madrid, Pz. Cardenal Cisneros 3, 28040 Madrid, Spain.

AAS 19-375

ATTITUDE DEPENDENT EVOLUTION OF ORBITS ABOUT ACTIVE COMETS

Mark J. Moretto[*] and Jay McMahon[†]

Spacecraft orbiting active comets are perturbed by gas drag from the coma. These gasses expand radially at about 0.5 km/s, much faster than orbital velocities that are on the order of meters per second. The resulting drag accelerations can be similar in magnitude to that of gravity and are thus important to model. Here we present an orbit averaging analysis of spacecraft motion about an active comet. The spacecraft will be modeled as a flat plate. This results in out-of-plane forces, enabling the use of natural dynamics for maneuvering. These dynamics can be leveraged for mission planning, operations, and science.

[View Full Paper]

[*] Graduate Student, Aerospace Engineering Sciences, University of Colorado Boulder, ECNT 320, 431 UCB, University of Colorado, Boulder, Colorado 80309-0431, USA.

[†] Assistant Professor, Aerospace Engineering Sciences, University of Colorado Boulder, ECNT 320, 431 UCB, University of Colorado, Boulder, Colorado 80309-0431, USA.

EFFECTS OF SPIN-ORBIT RESONANCE IN STABILITY FOR LOW ALTITUDE MARS ORBITS

Andres Dono[*] and Laura Plice[†]

Orbit stability has been the subject of thoughtful study in various celestial bodies. Increasing interest in Mars orbiters brings the question of natural decay in low altitude regimes. This paper studies shape alterations of low altitude Mars orbits by carrying out large sets of high fidelity numerical simulations. Results show that some initial configurations of the orbital elements gave perturbations that resulted in unstable orbits. The paper also studies the potential causes of the observed unstable regions. We computed theoretical spin-orbit resonances to study their implications in the stability at low altitudes. The resonances were tested at different initial Longitudes of the Ascending Node (LAN) values and orbit inclinations to investigate the potential existence of latitude/longitude implications on the stability. [View Full Paper]

[*] Trajectory Analyst, Millennium Engineering and Integration Services NASA Ames Research Center, Moffett Field, Mountain View, California 94035, USA.

[†] Systems Engineer V, Metis Technology Solutions, NASA/Ames Research Center, Mission Design Center, Moffett Field, Mountain View, California 94035, USA.

AAS 19-390

SECULAR ORBITAL ELEMENT VARIATIONS DUE TO CONTINUOUS LOW-THRUST CONTROL AND THIRD-BODY PERTURBATIONS

Xiaoyu Liu,* Colin McInnes† and Matteo Ceriotti‡

An analytical method is investigated to evaluate the low-thrust orbit dynamics of a spacecraft under the influence of third-body perturbations in the absence of resonance. The orbital evolution is formulated as a combination of Lagragian and Gaussian variational equations with two distinct perturbing accelerations. The third-body effects are described by Legendre polynomials and truncated up to second-order terms. Components of the control terms are represented as Fourier series in eccentric anomaly. Then the variational equations are averaged over its period to yield secular effects. The work is also presented in non-singular elements. Numerical simulation verifies the efficiency of the methodology. [View Full Paper]

* PhD Candidate, School of Engineering, University of Glasgow, Glasgow G12 8QQ, UK.
† Professor, School of Engineering, University of Glasgow, Glasgow G12 8QQ, UK.
‡ Lecturer, School of Engineering, University of Glasgow, Glasgow G12 8QQ, UK.

AAS 19-396

TRAJECTORY DESIGN IN THE CIRCULAR RESTRICTED THREE-BODY PROBLEM USING ARTIFICIAL INVARIANT MANIFOLDS

Yuki Oshima,[*] Mai Bando[†] and Shinji Hokamoto[‡]

This paper generalizes the invariant manifolds of unstable libration point orbits through the application of continuous thrust. Considering Jacobi constant of the end of invariant manifolds, an artificial periodic orbit around a libration point realizes heteroclinic connections between itself and an unforced periodic orbit with same Jacobi constant of the end of invariant manifolds. Heteroclinic connections between libration point orbits are constructed by detecting intersections of states of manifolds on the Poincaré map. We reveal low-energy spacecraft can transfer to some periodic orbits with different Jacobi constant. In addition, this paper defines New Jacobi constant of low-thrust spacecraft. By utilizing new Jacobi constant, we illustrate zero-velocity curves of low-thrust spacecraft and reveal that there is a crack of zero-velocity curves and spacecraft can pass the crack.
[View Full Paper]

[*] Student, Department of Aeronautics and Astronautics, Kyushu University, Fukuoka 819-0395, Japan.
[†] Associate Professor, Department of Aeronautics and Astronautics, Kyushu University, Fukuoka 819-0395, Japan.
[‡] Professor, Department of Aeronautics and Astronautics, Kyushu University, Fukuoka 819-0395, Japan.

VERY LONG ARC TIMING COEFFICIENT AND SOLAR LUNAR PLANETARY EPHEMERIS FILES AND APPLICATIONS

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

Precision orbit determination programs require time difference, polar motion parameter, solar, lunar, and planetary (SLP) ephemeris, and rotation matrix data. A single set of Timing Coefficient and SLP files valid from 1973 to 2169 is developed. The start date is dictated by the availability of the IERS data. The end date is dictated by the end of the DE 200 file. The DE 200 file provides information referred to the dynamical equator and equinox of 2000. The 196-year SLP files each require approximately 33 MB for data storage. The 196-year Timing Coefficient file requires consideration of the transition from observed to extrapolated data. Cumulative Distribution Function (CDF) plots are given for the Earth Rotation Parameter (ERP) errors. The performance of the 196-year files is explored. [View Full Paper]

[*] Zachary Folcik is Technical Staff at the MIT Lincoln Laboratory, Lexington, Massachusetts 02421, USA.

[†] Paul J. Cefola is Research Scientist, Department of Mechanical & Aerospace Engineering, University at Buffalo (SUNY), Amherst, New York 14260, USA. E-mail: paulcefo@buffalo.edu, paul.cefola@gmail.com. Fellow AAS. Also Consultant in Aerospace Systems, Spaceflight Mechanics, and Astrodynamics, Vineyard Haven, Massachusetts, USA.

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IDENTIFICATION OF FAMILIES OF PERIODIC ORBITS ABOVE/BELOW THE SOLAR SAIL EARTH-MOON LIBRATION POINTS

Jules Simo*

This paper addresses the problem of finding periodic solutions in the circular restricted three-body problem (CRTBP) with the Earth and Moon as the two primaries and the third massless body a solar sail. These orbits were accomplished by using an optimal choice of the sail pitch angle, which maximize the out-of-plane distance. Based upon the first-order approximation, an analytical formulation of the periodic orbits at linear order is presented. The approximate analytical solutions found are utilized in a numerical search to determine Lissajous trajectories in the full nonlinear model. In order to illustrate the near term and possible future orbits that can be achieved, we have generated the results for several values of the characteristic acceleration. [View Full Paper]

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

AAS 19-510

FEASIBILITY STUDY OF QUASI-FROZEN, NEAR-POLAR AND EXTREMELY LOW-ALTITUDE LUNAR ORBITS

Sandeep Kumar Singh,[*] Robyn Woollands,[†‡] Ehsan Taheri[§] and John L. Junkins[**]

Design of long-duration lunar orbiter missions is challenging due to the Moon's highly nonlinear gravity field and third-body perturbations induced by the Earth, Sun and other large bodies, on the orbiting spacecraft. The absence of a Lunar atmosphere, and hence the lack of orbital atmospheric drag, has encouraged mission designers to search for extremely low-altitude, stable, lunar orbits. In addition to the reduced amount of propellant required for station-keeping maneuvers, these orbits present great opportunities for unique scientific studies such as high resolution imaging and characterization of the polar ice deposits in deep craters. Mission planning for Lunar orbiters has historically suffered from inaccuracies, mainly due to the lack of an accurate Lunar gravity model, which resulted in severe deviations with respect to the spacecraft's nominal orbit. In 2012, JPL's Gravity Recovery and Interior Laboratory (GRAIL) mission mapped the Moon's gravity field with much improved accuracy, allowing future missions to be designed and flown with far better models. In this paper, we perform a station-keeping feasibility study for quasi-frozen, near-polar and extremely low-altitude orbits around the Moon with a high-fidelity lunar gravity model and when perturbations due to the Earth and Sun are taken into consideration. We study the trade-space between mission duration and ΔV budget considering impulsive maneuvers applied once every 3, 5 or 10 orbits. [View Full Paper]

[*] Graduate Research Assistant, Department of Aerospace Engineering, Texas A&M University, College Station, Texas 77843-3141, USA. AIAA Student Member.

[†] Mission Design Engineer, Jet Propulsion Laboratory, California Institute of Technology, Pasadena, California 91109, USA.

[‡] Adjunct Assistant Professor, Department of Aerospace Engineering, Texas A&M University, College Station, Texas 77843-3141, USA.

[§] Research Assistant Professor, Department of Aerospace Engineering, Texas A&M University, College Station, Texas 77843-3141, USA. AAS Member.

[**] Distinguished Professor, Department of Aerospace Engineering, Texas A&M University, College Station, Texas 77843-3141, USA. Honorary Fellow AAS.

A HIGH ORDER ANALYTIC CONTINUATION TECHNIQUE FOR THE PERTURBED TWO-BODY PROBLEM STATE TRANSITION MATRIX

Tahsinul Haque Tasif[*] and Tarek A. Elgohary[†]

In this work, the analytic continuation technique is used to derive the State Transition Matrix for the perturbed two body problem resulting in a fast, high precision solution that outperforms state of the art numerical methods. Analytic Continuation is a Taylor series based technique where two scalar Lagrange-like invariants (f = **r.r** and $gp = f^{-p/2}$) are defined and differentiated to an arbitrary order by using Leibniz product rule. These derivatives are used in a Taylor series expansion to obtain the solution. Previously, this method has been applied to several trajectory calculations, that resulted in high precision solutions for both position and velocity with a comparatively lower computational cost. As future work, the method will be expanded to solve the perturbed multi revolution Lambert's problem. [View Full Paper]

[*] Ph.D. Student, Mechanical and Aerospace Engineering, University of Central Florida, Orlando, Florida 32816 USA.
[†] Assistant Professor, Mechanical and Aerospace Engineering, University of Central Florida, Orlando, Florida 32816 USA.

ANALYSIS OF DISTURBANCE ANOMALY OF INTERPLANETARY MICRO-SPACECRAFT PROCYON

Satoshi Ikari,[*] Takaya Inamori,[†] Takahiro Ito[‡] and Ryu Funase[§]

In order to deeply understand orbital disturbances, the flight data of the PROCYON, which is the 50kg-class interplanetary micro-spacecraft was analyzed. In the telemetry data, we found two unexpected behaviors of angular momentum in Z-axis as compared with the accurate solar radiation pressure model. In order to clarify the causes of the angular momentum anomalies, several small disturbances like thermal radiation pressure, deformation of the structure, and interplanetary magnetic field effect, which are usually ignored are discussed in this study. The thermal radiation and deformation of the structure can explain the over-large Z-axis anomaly. The interplanetary magnetic field effect is correlated with the sudden change of Z-axis torque anomaly in several cases, but the cause of the anomaly is not completely revealed yet. [View Full Paper]

[*] Assistant Professor, Department of Aeronautics and Astronautics, the University of Tokyo, 7-3-1 Hongo, Bunkyo-ku, Tokyo, Japan 113-8656.
[†] Lecturer, Department of Micro-Nano Systems Engineering, Graduate School of Engineering Nagoya University, Furo-cho Chikusa-ku Nagoya, Japan 464-8603.
[‡] Researcher, ISAS, JAXA, 3-1-1 Yoshinodai, Chuo-ku, Sagamihara, Kanagawa, Japan, 252-5210.
[§] Associate Professor, Department of Aeronautics and Astronautics, the University of Tokyo, 7-3-1 Hongo, Bunkyo-ku, Tokyo, Japan 113-8656.

AAS 19-544

ANALYTICAL RADIAL ADAPTIVE METHOD FOR SPHERICAL HARMONICS GRAVITY MODELS

Ahmed M. Atallah,[*] Ahmad Bani Younes,[†] Robyn M. Woollands[‡] and John L. Junkins[§]

High precision propagation for satellites orbiting a large body with a highly nonlinear gravity field (planets, moons, asteroids) require accurate computation of the gravitational acceleration at each integration step. This is a computationally expensive operation that depends mainly on the orbit geometry and the accuracy to which the solution is required. High accuracy solutions require a large degree and order in the spherical harmonic series which significantly increases the computation time. In order to maintain a specific accuracy solution for a satellite in a highly elliptic orbit, a high gravity degree and order are needed near perigee and a lower degree and order are required at apogee. In this paper we present an analytic method for which the degree of the spherical harmonic series is automatically selected based on the desired solution accuracy specified by the user, and the instantaneous radial distance of the satellite from the Earth. We present results for several orbit test cases that demonstrate a significant speedup when using our analytical radial adaptive model for computing spherical harmonic gravity. [View Full Paper]

[*] PhD Student, San Diego State University (Joint Doctoral Program with University of California, San Diego), California 92093, USA.

[†] Assistant Professor, Department of Aerospace Engineering, San Diego State University, California 92093, USA.

[‡] Adjunct Assistant Professor, Texas A&M Aerospace Engineering, Texas 77843-3141, USA.

[§] University Distinguished Professor, Department of Aerospace Engineering, Texas A&M University, Texas 77843-3141, USA.

RETROGRADE TEARDROP ORBITS ABOUT ASTEROIDS: APPLICATION TO THE HAYABUSA2 MISSION

S. Kikuchi,[*] Y. Oki,[†] T. Saiki,[‡] Y. Takei,[§] H. Takeuchi,[**] G. Ono,[††] H. Ikeda[‡‡] and Y. Tsuda[§§]

This research investigates retrograde teardrop orbits (RTOs) about asteroids subject to strong solar radiation pressure. RTOs are closed orbits that are made periodic by introducing a deterministic impulsive delta-V within each period. This type of artificial periodic orbit provides high flexibility in orbit design compared with natural periodic orbits. RTOs are promising options for asteroid missions because of their stability and small delta-V values (on the order of 10 cm/s or less). This paper presents the dynamical theories of RTOs and possible applications for the Hayabusa2 mission. [View Full Paper]

[*] Research Associate, Institute of Space and Astronautical Science, Japan Aerospace Exploration Agency, 3-1-1 Yoshinodai, Chuo-ku, Sagamihara, Kanagawa, Japan 252-0222. E-mail: kikuchi.shota@ac.jaxa.jp.

[†] Ph.D. Candidate, Department of Aeronautics and Astronautics, The University of Tokyo, 7-3-1 Hongo, Bunkyo-ku, Tokyo, Japan 113-0033.

[‡] Assistant Professor, Institute of Space and Astronautical Science, Japan Aerospace Exploration Agency, 3-1-1 Yoshinodai, Chuo-ku, Sagamihara, Kanagawa, Japan 252-0222.

[§] Engineer, Institute of Space and Astronautical Science, Japan Aerospace Exploration Agency, 3-1-1 Yoshinodai, Chuo-ku, Sagamihara, Kanagawa, Japan 252-0222.

[**] Associate Professor, Institute of Space and Astronautical Science, Japan Aerospace Exploration Agency, 3-1-1 Yoshinodai, Chuo-ku, Sagamihara, Kanagawa, Japan 252-0222.

[††] Engineer, Institute of Space and Astronautical Science, Japan Aerospace Exploration Agency, 3-1-1 Yoshinodai, Chuo-ku, Sagamihara, Kanagawa, Japan 252-0222.

[‡‡] Engineer, Institute of Space and Astronautical Science, Japan Aerospace Exploration Agency, 3-1-1 Yoshinodai, Chuo-ku, Sagamihara, Kanagawa, Japan 252-0222.

[§§] Associate Professor, Institute of Space and Astronautical Science, Japan Aerospace Exploration Agency, 3-1-1 Yoshinodai, Chuo-ku, Sagamihara, Kanagawa, Japan 252-0222.

ANALYTIC PROBABILITY DENSITY MODEL OF SATELLITE SWARMS

Gong Yupeng,* Zhang Shijie† and Peng Xuan‡

A probability density model is developed to calculate the spatial distribution and coverage performance of satellite swarms on various orbits. Probability density function describes the probable distribution of a satellite. Consider the effects of gravitational perturbations and air drag, the evolutions of orbit radius, argument of latitude and right ascension of ascending node are given. By superposing the probability density functions in the solution space of orbit elements satisfying the coverage conditions, expectations and variances of the number of visible satellites at any location can be obtained. The method has higher accuracy when the number of satellites in swarm increases. [View Full Paper]

* Ph.D. Candidate, Research Center of Satellite Technology, Harbin Institute of Technology, 150000 Harbin, China.
† Professor, Research Center of Satellite Technology, Harbin Institute of Technology, 150000 Harbin, China.
‡ Ph.D. candidate, Control and Simulation Center, Harbin Institute of Technology, 150000 Harbin, China.

ATTITUDE DYNAMICS AND CONTROL

Session Chairs:

Session 3: Marcello Romano, Naval Postgraduate School

Session 7: Marco Ciarcia, South Dakota State University

The following papers were not available for publication:

AAS 19-202 Paper Withdrawn

AAS 19-275 Paper Withdrawn

SPACECRAFT ATTITUDE MOTION PLANNING ON SO(3) USING GRADIENT-BASED OPTIMIZATION

Fabio Celani* and Dennis Lucarelli†

The purpose of the present work is to perform spacecraft attitude motion planning so that a rest-to-rest rotation is achieved while satisfying pointing constraints. Attitude is represented on the group of three dimensional rotations SO(3). The motion planning is executed in two steps. In the first step, path-planning is performed by searching for a time behavior for the angular rates through the formulation of an optimal control problem solved with a gradient-based algorithm. In the second step, the actual input torque is simply determined by the use of inverse attitude dynamics. A numerical example is included to show the effectiveness of the method. From a practical point of view, the control torque resulting from the proposed approach is continuously differentiable and vanishes at its endpoints. [View Full Paper]

* Assistant Professor, School of Aerospace Engineering, Sapienza University of Rome, Via Salaria 851 00138 Roma Italy. E-mail: E-mail: fabio.celani@uniroma1.it.

† Research Associate Professor, Department of Physics, American University, 4400 Massachusetts Ave NW, Washington, DC 20016. E-mail: dgl@american.edu.

CONFIGURATION OPTIMIZATION OF 0-1 SUN SENSORS FOR SUN VECTOR DETERMINATION

Shijie Zhang,* Botian Zhou† and Shiqiang Wang‡

Sun vector is vital for the determination of satellite attitude, which can be coarsely estimated utilizing 0-1 sun sensors. However, the configuration of sun sensors varied from one to another and there is no standard theory for designing the configuration. Therefore, in this paper, the optimization model of the configuration of 0-1 sun sensors was first established, where the reliability, precision, cost, and the redundancy of sun vector determination were in consideration. Then the configuration was optimized and the results were presented. Finally, the sun vector determination error and its distribution were analyzed and the robustness was verified. [View Full Paper]

* Professor, Research Center of Satellite Technology, Harbin Institute of Technology, 150000, Harbin, China.
† Ph.D. Student, Research Center of Satellite Technology, Harbin Institute of Technology, 150000, Harbin, China.
‡ Ph.D. Student, Research Center of Satellite Technology, Harbin Institute of Technology, 150000, Harbin, China.

AAS 19-257

INNOVATIVE GUIDANCE AND CONTROL DESIGN OF THE VERSATILE ORBIT TRANSFER SPACE VEHICLE OF THE EPSILON ROCKET

Yasuhiro Morita,* Ryoma Yamashiro,† Hiroyuki Yamaguchi,‡ Kensaku Tanaka§ and Hirohito Ohtsuka**

This paper deals with the innovative guidance and control design of the versatile orbit transfer space vehicle that acts as the upper stage of the Epsilon rocket. Its objective is to place small satellites into orbits with significantly high accuracy and flexibility. The primary issue is the high accuracy guidance and control under the relatively low thrust acceleration (long burn time) and relatively large initial orbit dispersion. A rhumb line control and a guidance strategy, the extended long-time velocity increment cut-off guidance law (LVIC), is utilized to tackle this challenge. [View Full Paper]

* Professor, Space Flight Systems, ISAS/JAXA, 3-1-1 Yoshinodai, Chuo, Sagamihara, Kanagawa 252-5210, Japan.
† Associate Senior Engineer (Researcher), Epsilon Launch Vehicle, JAXA, 2-1-1 Sengen, Tsukuba, Ibaraki, 305-8505, Japan.
‡ Associate Senior Engineer, Epsilon Launch Vehicle, JAXA2-1-1 Sengen, Tsukuba, Ibaraki, 305-8505, Japan.
§ IHI Aerospace CO., LTD., 900 Fujiki, Tomioka, Gunma 370-2398, Japan.
** IHI Aerospace CO., LTD., 900 Fujiki, Tomioka, Gunma 370-2398, Japan.

AAS 19-283

WAYPOINT FOLLOWING DYNAMICS OF A QUATERNION ERROR FEEDBACK ATTITUDE CONTROL SYSTEM

Mark Karpenko,[*] Julie K. Halverson[†] and Rebecca Besser[‡]

Closed-loop attitude steering can be used to implement a non-standard attitude maneuver by using a conventional attitude control system to track a non-standard attitude profile. The idea has been employed to perform zero-propellant maneuvers on the International Space Station and minimum time maneuvers on NASA's TRACE space telescope. A challenge for operational implementation of the idea is the finite capacity of a space vehicle's command storage buffer. One approach to mitigate the problem is to downsample-and-hold the attitude commands as a set of waypoints for the attitude control system to follow. In this paper, we explore the waypoint following dynamics of a quaternion error feedback control law for downsample-and-hold. It is shown that downsample-and-hold induces a ripple between downsamples that causes the satellite angular rate to significantly overshoot the desired limit. Analysis in the z-domain is carried out in order to understand the phenomenon. An interpolating Chebyshev-type filter is proposed that allows attitude commands to be encoded in terms of a set of filter coefficients. Using the interpolating filter, commands can be issued at the ACS rate but with significantly reduced memory requirements. The attitude control system of NASA's Lunar Reconnaissance Orbiter is used as an example to illustrate the behavior of a practical attitude control system. [View Full Paper]

[*] Research Associate Professor and Corresponding Author, Department of Mechanical and Aerospace Engineering, Naval Postgraduate School, Monterey, California 93943, USA. E-mail: mkarpenk@nps.edu.
[†] Lead Systems Engineer, Space Sciences Mission Operations, NASA Goddard Space Flight Center, Greenbelt, Maryland 20771, USA.
[‡] Systems Engineer, KBRWyle Government Services, Huntsville, Alabama 35806, USA; formerly at NASA/GSFC.

AAS 19-287

ATTITUDE MANEUVER DESIGN FOR PLANAR SPACE SOLAR POWER SATELLITES

Michael A. Marshall,* Ashish Goel† and Sergio Pellegrino‡

This paper investigates the attitude dynamics of a planar space solar power satellite (SSPS) by formulating the power-optimal guidance problem as a nonlinear trajectory optimization problem. The power-optimal guidance problem determines the orientation of an SSPS throughout its orbit that maximizes the amount of power transmitted to Earth. This transmitted power is a function of the relative geometry between the SSPS, the Sun, and the receiving station. Hence, it is inherently coupled to the attitude of the SSPS, i.e., the orientation that maximizes power transmission changes as the relative geometry changes. We first approximate the discretized trajectory optimization problem as a quadratic program (QP). We then solve the QP to obtain attitude trajectory designs for various orbits. These solutions highlight how maximizing transmitted power typically requires large slew maneuvers. Ultimately, by quantifying control and propellant requirements for various orbits, we emphasize how maneuver dynamics play an important role in SSPS design. [View Full Paper]

* Graduate Research Assistant, Graduate Aerospace Laboratories, 1200 E. California Blvd., Mail Code 105-50, Pasadena, California 91125. E-mail: mmarshall@caltech.edu.

† Postdoctoral Researcher, Jet Propulsion Laboratory, 4800 Oak Grove Dr., Pasadena, California 91109. E-mail: ashish.goel@jpl.nasa.gov.

‡ Joyce and Kent Kresa Professor of Aerospace and Civil Engineering; Jet Propulsion Laboratory Senior Research Scientist; Co-Director, Space-Based Solar Power Project, Graduate Aerospace Laboratories, 1200 E. California Blvd., Mail Code 105-50, Pasadena, California 91125. E-mail: sergiop@caltech.edu.

AAS 19-296

ROTATIONS, TRANSFORMATIONS, LEFT QUATERNIONS, RIGHT QUATERNIONS?*

Renato Zanetti†

This paper surveys the two fundamental possible choices in representing the attitude of an aerospace vehicle: active and passive rotations. The consequences of the choice between the two are detailed for the two most common attitude parameterizations, a three-by-three orthogonal matrix and the quaternion. Successive rotations are also reviewed in this context as well as the attitude kinematic equations. [View Full Paper]

* This paper was submitted to the Journal of the Astronautical Sciences for publication consideration.

† Assistant Professor, Department of Aerospace Engineering and Engineering Mechanics, The University of Texas at Austin, Mail Code C0600, Austin Texas 78712, USA.

PREDICTING TIME-OPTIMAL SLEWS ACROSS MULTIPLE SPACECRAFT WITH INERTIA RATIOS

Jeffery T. King[*] and Yash Khatavkar[†]

A common goal of satellite control systems is to reduce the time required to change a spacecraft's attitude, maximizing its mission capability. Time-optimal attitude control increases the agility of satellites such as imaging satellites thus allowing a greater frequency of image collection. Eigenaxis based maneuvering, though common in industry and academia, fails to produce the minimum-time solution for actual satellites. Solving the optimal control problem is often challenging and requires evaluating multiple maneuver paths to ensure the shortest path is found for each spacecraft configuration. One of the primary difficulties in predicting optimal control benefits stems from the wide range of satellite configurations and the infinite variation in inertia. This paper aims to facilitate quicker comparison of various satellite configurations by demonstrating that inertia ratios can be used to predict satellite agility performance on a relative scale and provides a simple and effective way to compare of the benefit of optimal control maneuvering for any spacecraft. This relationship was validated by analyzing maneuvers in five different test cases with four spacecraft. [View Full Paper]

[*] Assistant Professor and corresponding author, Aerospace Engineering Department, United States Naval Academy, Annapolis, Maryland 21402, USA. E-mail: jking@usna.edu.
[†] Undergraduate Student, Aerospace Engineering Department, United States Naval Academy, Annapolis, Maryland 21402, USA.

UNCERTAINTY QUANTIFICATION AND ANALYSIS OF DYNAMICAL SYSTEMS WITH INVARIANTS

Anant A. Joshi[*] and Kamesh Subbarao[†]

This paper considers uncertainty quantification in systems perturbed by stochastic disturbances, in particular, Gaussian white noise. The main focus of this work is on describing the time evolution of statistical moments of certain invariants (for instance total energy and magnitude of angular momentum) for such systems. A first case study for the attitude dynamics of a rigid body is presented where it is shown that these techniques offer a closed form representation of the evolution of the first and second moments of the kinetic energy of the resulting stochastic dynamical system. A second case study of a two body problem is presented in which bounds on the first and second moments of the angular momentum are presented. [View Full Paper]

[*] Undergraduate Student, Department of Mechanical Engineering, Indian Institute of Technology Bombay 400076, India.
[†] Associate Professor, Department of Mechanical and Aerospace Engineering, The University of Texas at Arlington, Texas 76010, USA.

AAS 19-374

NUMERICAL RESULTS ON THE GENERAL TIME-OPTIMAL REST-TO-REST THREE-AXIS REORIENTATION OF A RIGID SPACECRAFT

Alanna Sharp[*] and Marcello Romano[†]

The time-optimal results to the rest-to-rest three-axis reorientation of a rigid spacecraft are presented here as an equidistant conic projection with respect to the eigenvector sphere for all possible rest-to-rest reorientation maneuvers of a given slew angle. The pseudospectral method is used to obtain the numerical results over a selection of azimuths and elevations within the first octant of the eigenvector sphere. The equidistant conic projection method used in cartography then translates the three dimensional eigenvector coordinates to a cone surface surrounding the eigenvector sphere. The result is the interpolated solution set to equally space polar coordinates on a flat quadrant, given a chosen slew angle and inertial assumptions. Additionally, the latitude-longitude representation is applied to the attitude history of the principle axes of rotation of the rigid spacecraft as a trajectory mapping method. All projections are applicable to spherically symmetric, cylindrically symmetric, and triaxial spacecraft, and case studies are presented for each. All presented methods may be applied to represent other cost functionals and constraints as well. [View Full Paper]

[*] PhD Student, Spacecraft Robotics Laboratory, Naval Postgraduate School, 1 University Circle, Monterey, California 93940, USA.
[†] Professor, Spacecraft Robotics Laboratory, Naval Postgraduate School.

AAS 19-399

FAULT POINTS DETECTION FOR LARGE SOLAR PANEL BASED ON PHOTOGRAMMETRY

Hongwen Wang,[*] Rui Zhong[†] and Pengjie Li[‡]

In this paper, a large solar panel model is established using finite element software and modal analysis is conducted. A combined selecting method of optical measuring points is designed based on the modal information provided by MSC.Patran/Nastran. Dynamic simulation of the solar panel is performed using Matlab/Simulink. The vibration of the solar panel is excited by pulse input, and the displacement of the measuring points are collected for modal identification. White noise corresponding to the available vision measurement is added considering the displacement acquisition by photogrammetry. Two failure modes are investigated, which are data contamination and data missing. This paper utilizes principal components analysis (PCA) to transform data to another feature space and detects the location of fault point with the statistic SPE. This research may help to modify the existing scheme of optical measuring points and identify modal parameters intelligently. [View Full Paper]

[*] Master Candidate, School of Astronautics, No. 37 Xueyuan Road, Haidian District, Beijing, 100191.
[†] Associate Professor, School of Astronautics, No. 37 Xueyuan Road, Haidian District, Beijing, 100191.
[‡] Master Candidate, School of Astronautics, No. 37 Xueyuan Road, Haidian District, Beijing, 100191.

REMOVING RATE UNOBSERVABILITY IN SUN-HEADING FILTERS WITHOUT RATE GYROS

Thibaud Teil,[*] Hanspeter Schaub[†] and Scott Piggott[‡]

In a sun-heading determination scenario Coarse Sun-Sensors (CSS) can be paired with rate gyros in order to estimate sunline direction and rotation rate. These paired measurements allow for a fully observable sun-heading state vector. However, relying solely on CSS measurements for sun-heading and spacecraft rotation rate estimation is advantageous in scenarios where reliance on the fewest number of devices is desired. Here the challenge is to find a robust method for heading determination relying neither on rate gyros nor on spacecraft dynamics. In such a scenario, the rotation rate of the spacecraft is estimated in order to provide state derivative control or simply for better sun-heading estimation. Therefore, the state vector is traditionally the sun direction vector and its time derivative as seen by the body frame. A novel sun-heading filter is derived which estimates only the observable components of the body rate vector since the rate about the sun heading axis remains unobservable. By switching between kinematic formulations, it provides not only better sun-heading estimates, but also a partial body rate estimate. The new CSS filter provides the sun heading in a non-singular manner and estimates the observable component of the angular velocity vector. Both an extended Kalman filter formulation and a square-root unscented filter formulation are developed. The new filter is compared to two filters for gyro-less sun-heading estimation. One comparison filter uses a projection method to remove the unobservable rate component and another comparison filter uses numerical heading differences to estimate a rotation rate. The filters vary in state vectors, kinematics, and filter types, with the goal of controlling or removing non-observability. In order to compare the behavior of the set of sun-sensing algorithms, a modular filtering architecture is used and its utility is demonstrated. By incorporating this architecture in the Basilisk astrodynamics software package filter performances are compared through realistic scenarios. [View Full Paper]

[*] Graduate Research Assistant, Aerospace Engineering Sciences, University of Colorado Boulder.
[†] Glenn L. Murphy Chair of Engineering, Department of Aerospace Engineering Sciences, University of Colorado, 431 UCB, Colorado Center for Astrodynamics Research, Boulder, Colorado 80309-0431. AAS Fellow.
[‡] ADCS Integrated Simulation Software Lead, Laboratory for Atmospheric and Space Physics, University of Colorado Boulder.

AAS 19-473

ANGULAR CORRELATION USING ROGERS-SZEGÖ-CHAOS

Christine L. Schmid* and Kyle J. DeMars†

Polynomial chaos expresses a probability density function (pdf) as a linear combination of basis polynomials. If the density and basis polynomials are over the same field, any set of basis polynomials can describe the pdf; however, the most logical choice of polynomials is the family that is orthogonal with respect to the pdf. This problem is well-studied over the field of real numbers and has been shown to be valid for the complex unit circle in one dimension. The current framework for circular polynomial chaos is extended to multiple angular dimensions with the inclusion of correlation terms. Uncertainty propagation of heading angle and angular velocity is investigated using polynomial chaos and compared against Monte Carlo simulation. [View Full Paper]

* Graduate Student, Department of Mechanical and Aerospace Engineering, Missouri University of Science and Technology, Rolla, Missouri 65409, USA.
† Assistant Professor, Department of Mechanical and Aerospace Engineering, Missouri University of Science and Technology, Rolla, Missouri 65409, USA.

DISCRETE-TIME ITERATIVE LEARNING CONTROL FOR NONLINEAR SYSTEMS BASED ON FEEDBACK LINEARIZATION

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

Iterative learning control (ILC) learns to track a pre-defined maneuver with high accuracy through practice. It aims to approach the hardware reproducibility error level, which is usually beyond the accuracy of the system model used in the learning process. ILC can be used in spacecraft fine pointing sensors doing repeated scanning maneuvers. This paper considers use of feedback linearization in ILC, coupled with sophisticated linear ILC laws. Previous papers in this seried study other methods of extending ILC to nonlinear systems, using linearlization, and bilineariarization. Comparison is made of the three approaches. Feedback linearization has the advantage that it provides a global linear model to the ILC law while linearization and bilinearization are local models. Numerical examples demonstrate the comparison of these ILC methods for nonlinear systems, suggesting that feedback linearization based ILC can exhibit faster learning. [View Full Paper]

[*] PhD, Mechanical Engineering, Columbia University, 500vWest 120th Street, MC4703, New York, New York 10027, USA.
[†] Thayer School of Engineering, Dartmouth College, Hanover, New Hampshire 03755, USA.
[‡] Mechanical Engineering, Columbia University, 500 West 120th Street, MC4703, New York, New York 10027, USA.

CONTROL OF AN EARTH-BASED SATELLITE TEST PLATFORM THROUGH VISION BASED POSITION MEASUREMENT

Sital Khatiwada,* Andrew M. Masters,† Aaron M. Cantara,‡ Michael Goulet§ and May-Win Thein**

In this paper, the authors propose using multirotor Unmanned Aerial Vehicles (UAVs) as an economical option of testing and evaluating satellite control algorithms on an Earth-based platform. To improve a multirotor's capacity to mimic satellites, a robust control scheme is designed and tested to assess its capabilities. An in-house vision system is fabricated for state monitoring. The system is integrated with the multirotor platform and evaluated for accuracy and precision. Numerical and experimental results provide meaningful qualitative data, granting insight on methods to improve multirotor capabilities to serve as low-cost spacecraft test beds. [View Full Paper]

* Graduate Student, Mechanical Engineering, University of New Hampshire, 33 Academic Way, Durham, New Hampshire 03824, USA.
† Undergraduate Student, Mechanical Engineering, University of New Hampshire, 33 Academic Way, Durham, New Hampshire 03824, USA.
‡ Undergraduate Student, Mechanical Engineering, University of New Hampshire, 33 Academic Way, Durham, New Hampshire 03824, USA.
§ Undergraduate Student, Computer Science, University of New Hampshire, 33 Academic Way, Durham, New Hampshire 03824, USA.
** Associate Professor, Mechanical Engineering, University of New Hampshire, 33 Academic Way, Durham, New Hampshire 03824, USA.

SPACECRAFT RADIATION PRESSURE USING COMPLEX BIDIRECTIONAL-REFLECTANCE DISTRIBUTION FUNCTIONS ON GRAPHICS PROCESSING UNIT

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

A faster-than-realtime approach is studied to compute the solar radiation pressure forces and torques on a complex time-varying spacecraft model. The method employs ray-tracing techniques, developed in the graphics rendering discipline, to resolve spacecraft self-shadowing, self-reflections and complex surface material optical characteristics at faster than real-time computation speed. The primary algorithmic components of the ray-tracing process which contribute to the method's computational efficiency are described, including enhancements which take advantage of the fact that the end goal is an accurate force evaluation, not a visual image. A Monte Carlo importance sampling integration method is used to evaluate the integral of complex bidirectional reflectance distribution functions (BRDF) models. The modeling approach process is implemented using C++ and OpenCL and executed on a consumer grade graphics processing unit. A model validation is presented comparing computed values to both the analytic cannonball model and ray traced LAGEOS II spacecraft model. The effects on translational motion due to various BRDF models is compared. [View Full Paper]

[*] Graduate Research Assistant, Aerospace Engineering, University of Colorado, Boulder.
[†] Professor and Glenn L. Murphy Endowed Chair of Engineering, Aerospace Engineering Sciences, University of Colorado at Boulder, 431 UCB, Colorado Center for Astrodynamics Research, Boulder, Colorado 80309-0431, USA. AAS Fellow.

ATTITUDE CONTROL AND ORBIT DETERMINATION OF A CREWED SPACECRAFT WITH LUNAR LANDER IN NEAR RECTILINEAR HALO ORBIT

Clark P. Newman,* Ryan Sieling,† Diane C. Davis‡ and Ryan J. Whitley§

NASA's Gateway program plans to place a crew-tended spacecraft in cislunar Near Rectilinear Halo Orbit (NRHO). The craft will support arrivals of the crewed Orion spacecraft and the undocking and return of a crewed lunar lander. Attitude control during Gateway assembly and with the addition of a lunar lander is investigated. Perturbations on the Gateway from the docking and undocking of Orion and the lander are considered. Orbit determination accuracy is explored, with Deep Space Network (DSN) tracking supplemented with optical crater measurements to analyze the possible benefit in solution accuracy and/or DSN scheduling relief. [View Full Paper]

* Senior Systems Engineer, a.i. solutions, Inc., 2224 Bay Area Blvd., Houston Texas 77058, USA.
† Systems Engineer, CACI NSS, Inc., 2224 Bay Area Blvd., Houston Texas 77058, USA.
‡ Principal Systems Engineer, a.i. solutions, Inc., 2224 Bay Area Blvd., Houston Texas 77058, USA.
§ Deputy Systems Integration Manager, Exploration Mission Planning Office, NASA Johnson Space Center, 2101 NASA Parkway, Houston, Texas 77058 USA.

AAS 19-572

BASIS FUNCTION ITERATIVE LEARNING CONTROL: LIMITING ACCUMULATION IN UNADDRESSED ERROR SPACE WITH SINGULAR VECTOR BASIS FUNCTIONS

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

Iterative Learning Control (ILC) aims to produce high precision tracking of a trajectory learning from repeating trials. The approach can significantly improve the performance of control systems that repeatedly execute a task. Spacecraft applications include repeated scanning with a fine pointing sensor. Basis function ILC restricts the input to a subspace, and aims for zero error in a subspace of the output. The advantages include, reduced computation, avoiding the common difficulty of an unstable inverse for many digital systems, avoiding difficulty from unmodeled high frequency dynamics, and avoiding the need for a zero-phase low-pass filter for robustification. This paper identifies a potentially serious issue, that while the ILC is converging to zero error in the chosen or addressed part of the output error space, error can be accumulating in the unaddressed part of the space. A formula is derived to analyze the accumulation, and give the final value of the error. A method to pick the basis functions is presented that can avoid this accumulation. The concept of matched basis functions is presented, and if the model used is correct, there is no accumulation. The basis functions are chosen from the input and the output singular vectors of the singular value decomposition of the input-output matrix of Markov parameters. These basis functions are orthogonal and mapped one to one. They are related to the system frequency response which helps guide the designer in the choice of which singular vectors to include. The design can be made by finding the Markov parameters using the OKID algorithm directly from data. There is no need to identify a transfer function model. [View Full Paper]

* Ph.D. Candidate, Mechanical Engineering Department, Columbia University, 500 West 120th Street, New York, New York 10027, USA.
† Professor of Mechanical Engineering, Columbia University, 500 West 120th St. New York, New York 10027, USA.
‡ Associate Professor, Thayer School of Engineering, Dartmouth College, Hanover, New Hampshire 03755, USA.

ARTIFICIAL INTELLIGENCE IN ASTRODYNAMICS

Session Chairs:

Session 5: Roberto Furfaro, The University of Arizona

REAL-TIME OPTIMAL CONTROL FOR IRREGULAR ASTEROID LANDINGS USING DEEP NEURAL NETWORKS

Lin Cheng,[*] Zhenbo Wang,[†] Yu Song[‡] and Fanghua Jiang[§]

To improve the autonomy and intelligence of asteroid landings, a real-time optimal control approach is proposed using deep neural networks (DNN) for asteroid landing problems wherein the developed DNN-based landing controller is capable of steering the lander to a preselected landing site with high robustness to initial conditions. First, to significantly reduce the time consumption of gravity calculation, DNNs are used to approximate the irregular gravitational field of asteroids based on samples from a polyhedral method. Then, an improved indirect method is presented to solve the time-optimal landing problems with high computational efficiency by taking advantage of the designed gravity approximation method and a homotopy technique. Furthermore, five DNNs are developed to learn the functional relationship between the state and optimal actions obtained by the indirect method, and the resulting DNNs can generate the optimal control instructions in real time because there is no longer need to solve the optimal landing problems onboard. Finally, a DNN-based landing controller composed of these five DNNs is devised to achieve the real-time optimal control for asteroid landings. Simulation results of the time-optimal landing for Eros are given to substantiate the effectiveness of these techniques and illustrate the solution optimality and robustness of the developed DNN-based optimal landing controller. [View Full Paper]

[*] Postdoctor, School of Aerospace Engineering, Tsinghua University, 10084 Beijing, China.

[†] Assistant Professor, Department of Mechanical, Aerospace, and Biomedical Engineering, University of Tennessee, Knoxville, Tennessee 37996, USA.

[‡] Ph.D. Candidate, School of Aerospace Engineering, Tsinghua University, 10084 Beijing, China.

[§] **Corresponding Author**, Associate Professor, School of Aerospace Engineering, Tsinghua University, 10084 Beijing, China.

DEEP NEURAL NETWORKS FOR OPTIMAL LOW-THRUST ORBIT RAISING

Haiyang Li,[*] Francesco Topputo[†] and Hexi Baoyin[‡]

Geostationary Earth orbit (GEO) satellites are of great significance in the space market. Low-thrust propulsion has been highly developed in the last decades because it is fuel saving. Therefore, the design of GEO satellites is rapidly changing from classic high-thrust propulsion more and more toward low-thrust propulsion. However, the transfer time will be quite long using low-thrust propulsion and it will be very expensive if the ground supports the whole orbit raising. Therefore, autonomous orbit raising is necessary. Deep neural networks are trained to learn the optimal control. Results show that DNNs can be applied in this long-duration optimal control problem and have excellent performance. [View Full Paper]

[*] Visiting PhD, Department of Aerospace Science and Technology, haiyang.li@mail.polimi.it, Politecnico di Milano, Milan, 20156, Italy; PhD Candidate, School of Aerospace Engineering, Tsinghua University, Beijing, 100084, China.
[†] Assistant Professor, Department of Aerospace Science and Technology, francesco.topputo@polimi.it, AAS Technical Chair, Politecnico di Milano, Milan, 20156, Italy.
[‡] Professor, School of Aerospace Engineering; baoyin@tsinghua.edu.cn. Senior member AIAA, Tsinghua University, Beijing, China, 100084, China.

FAST ESTIMATION OF GRAVITATIONAL FIELD OF IRREGULAR ASTEROIDS BASED ON DEEP NEURAL NETWORK AND ITS APPLICATION

Yu Song,[*] Lin Cheng[†] and Shengping Gong[‡]

A novel approach is proposed to fast estimate the gravitational field of the irregular asteroid by the DNN, and its application in the study of asteroid landing problem is investigated in this work. The traditional method of describing the gravitational field of irregular asteroids has obvious shortcomings in computational efficiency. For a fast estimation of the gravitational field of the irregular asteroid, a DNN architecture are built and optimized. After training and validation of the DNN, the test of the gravitational acceleration and gradient output of the DNN gravitational model is conducted. The gradient estimation of the gravitational field based on the DNN gravitational will be derived to adapt to the orbital dynamic analysis of the spacecraft near the asteroids. Based on the DNN gravitational model, we will demonstrate the application taking the fuel-optimal landing problem as an example. A double homotopy method is proposed to solve the fuel-optimal landing problem fast. The numerical cases are used to verify the proposed method.

[View Full Paper]

[*] Ph.D. Student, School of Aerospace Engineering, Tsinghua University, 100084 Beijing, China.
[†] Post-doctoral Fellow, School of Aerospace Engineering, Tsinghua University, 100084 Beijing, China.
[‡] Associate Professor, School of Aerospace Engineering, Tsinghua University, 100084 Beijing, China.

ACTOR-CRITIC REINFORCEMENT LEARNING APPROACH TO RELATIVE MOTION GUIDANCE IN NEAR-RECTILINEAR ORBIT

Andrea Scorsoglio,* Roberto Furfaro,† Richard Linares‡ and Mauro Massari§

This paper aims a developing a new feedback guidance algorithm for docking maneuvers in the cislunar environment. In particular, the goal is to create an algorithm that is light-weight, closed-loop and capable of taking path constraints into account. The problem has been solved starting from the well know Zero-Effort-Miss/Zero-Effort-Velocity (ZEM/ZEV) guidance using machine learning to improve its capabilities and widen its field of application. The algorithm has been developed in the circular restricted three body problem (CRTBP) framework for Near Rectilinear Orbits (NRO) in the Earth-Moon system but the results can be easily generalized to many more guidance problems. The results are satisfactory and show that reinforcement learning can be effectively used to solve constrained relative spacecraft guidance problems. [View Full Paper]

* PhD Student, System & Industrial Engineering Department, University of Arizona, 1127 E. James E. Rogers Way, Tucson, Arizona 85721, USA.

† Professor, System & Industrial Engineering Department, University of Arizona, 1127 E. James E. Rogers Way, Tucson, Arizona 85721, USA.

‡ Charles Stark Draper Assistant Professor, Department of Aeronautics and Astronautics, Massachusetts Institute of Technology, 77 Massachusetts Avenue Cambridge, Massachusetts 02139, USA. Senior Member AIAA, E-mail: linaresr@mit.edu.

§ Professor, Aerospace Science and Technology Department, Politecnico di Milano, Piazza Leonardo da Vinci 32, 20133 Milano, Italy.

SPACECRAFT DECISION-MAKING AUTONOMY USING DEEP REINFORCEMENT LEARNING

Andrew Harris,[*] Thibaud Teil[†] and Hanspeter Schaub[‡]

The high cost of space mission operations has motivated several space agencies to prioritize the development of autonomous spacecraft control techniques. “Learning” agents present one manner in which autonomous spacecraft can adapt to changing hardware capabilities, environmental parameters, or mission objectives while minimizing dependence on ground intervention. This work considers the frameworks and tools of deep reinforcement learning to address high-level mission planning and decision-making problems for autonomous spacecraft, under the assumption that sub-problems have been addressed through design. Two representative problems reflecting challenges of autonomous orbit insertion and science operations planning, respectively, are presented as Partially-Observable Markov Decision Processes (POMDP) and addressed with Deep Reinforcement Learners to demonstrate the benefits, pitfalls, considerations inherent to this approach. Sensitivity to initial conditions and learning strategy are discussed and analyzed. Results from selected problems demonstrate the use of reinforcement learning to improve or fine-tune prior policies within a mode-oriented paradigm while maintaining robustness to uncertain environmental parameters. [View Full Paper]

[*] Research Assistant, Ann and H.J. Smead Department of Aerospace Engineering Sciences, University of Colorado Boulder, Boulder, Colorado 80309, USA.
[†] Research Assistant, Ann and H.J. Smead Department of Aerospace Engineering Sciences, University of Colorado Boulder, Boulder, Colorado 80309, USA.
[‡] Glenn L. Murphy Chair of Engineering, Smead Department of Aerospace Engineering Sciences, University of Colorado, 431 UCB, Colorado Center for Astrodynamics Research, Boulder, Colorado 80309-0431, USA. AAS Fellow.

AAS 19-462

SPACECRAFT RENDEZVOUS GUIDANCE IN CLUTTERED ENVIRONMENTS VIA REINFORCEMENT LEARNING

Jacob Broida* and Richard Linares†

This paper investigates the use of Reinforcement Learning for closed-loop control applied to satellite rendezvous missions. In particular, we implement and evaluate Proximal Policy Optimization (PPO) to develop a control policy to move one satellite in a relative orbit reference frame into docking position with another. This method parameterizes the agents policy using a neural network, then uses data sampled from repeated simulations in the context of a reward function to perform gradient descent on the parameterized policy. After sufficient training, we evaluate the performance of PPO developed policies in a simulated satellite rendezvous environment including a keep-out zone to protect against collisions. The simulations considered for this work model the three-Degree-of-Freedom (3-DoF) dynamics but future work will consider six-Degree-of-Freedom (6-DoF). Our experimental results show that the agent was able to maneuver to within centimeters of the intended target without collision. [View Full Paper]

* Graduate Student, Department of Aeronautics and Astronautics, Massachusetts Institute of Technology, Cambridge, Massachusetts 02139, USA. E-mail: broidaj@mit.edu. Student Member AIAA.

† Charles Stark Draper Assistant Professor, Department of Aeronautics and Astronautics, Massachusetts Institute of Technology, Cambridge, Massachusetts 02139, USA. E-mail: linaresr@mit.edu. Senior Member AIAA.

AAS 19-479

INVESTIGATION OF DIFFERENT NEURAL NETWORK ARCHITECTURES FOR DYNAMIC SYSTEM IDENTIFICATION: APPLICATIONS TO ORBITAL MECHANICS

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

Machine learning and new AI algorithms inspire the scientific community to explore and develop new approaches for discovery of scientific laws and governing equations for complex physical and nonlinear dynamical systems. The question on how well deep learning approaches can approximate a given set of input data is difficult to answer. Considering the unperturbed two-body problem, this paper investigates the approximation and prediction capabilities of three types of neural networks: Feed-Forward, Residual and Deep Residual. Used in a purely recurrent model, these three architectures are able to produce highly satisfactory performances, very close to numerical integration tolerances. Furthermore, the effect of the mathematical representation (i.e. coordinate system) on the learning process is also investigated. From numerical results, it can be inferred that NN were able to better learn inherent dynamics characteristics in spherical coordinates without any apriori information than in Cartesian coordinate system. It is shown that a simple NN architecture is able to learn the symmetry of the central force and reproduce the conservation of the constants of the motion. [View Full Paper]

* Graduate Student, Department of Aerospace Engineering, The Pennsylvania State University, University Park, Pennsylvania 16802, USA. E-mail: djg76@psu.edu.

† Associate Professor, Department of Aerospace Engineering, The Pennsylvania State University, University Park, Pennsylvania 16802, USA. E-mail: psingla@psu.edu. AIAA Associate Fellow, AAS Fellow.

‡ Professor, Department of Aerospace Engineering, Pennsylvania State University, University Park, Pennsylvania 16802, USA. E-mail: rgmelton@psu.edu. AIAA Associate Fellow, AAS Fellow.

AAS 19-537

ADAPTIVE CONTROL BY REINFORCEMENT LEARNING FOR SPACECRAFT ATTITUDE CONTROL

Mohammad Ramadan*and Ahmad Bani Younes†

An adaptive controller based on Reinforcement Learning is presented. The Approximate Dynamic Programming (ADP) is basically used to approximate the cost-to-go term of the Dynamic Programming (DP) to avoid the so-called curse of dimensionality. Rather than approximating the cost-to-go term, our approach directly uses the optimal trajectories of simpler Ordinary Differential Equations (ODEs), forcing the controller to serve as a nonlinear feedback controller. The system trajectory is forced to follow the optimal trajectory of the chosen ODEs. From the preliminary results, our approach can be used online and reach convergence ’early enough’, allowing the following time to be used to approximate the cost-to-go term using a greedy policy. This method is applied on a spacecraft attitude control system to demonstrate its effectiveness, which is expected to be proudly useful for control solutions of several nonlinear models and real-time applications.

[View Full Paper]

* PhD Student, Aerospace Engineering Department, San Diego State University (Joint Doctoral Program with University of California, San Diego), San Diego, California.
† Assistant Professor, Department of Aerospace Engineering, San Diego State University, San Diego, California 92182, USA.

LOW-THRUST OPTIMAL CONTROL VIA REINFORCEMENT LEARNING

Daniel Miller[*] and Richard Linares[†]

The task of finding low-thrust trajectories in cis-lunar space in real-time and onboard spacecraft is an open problem. While traditional optimization techniques are capable of finding low-thrust trajectories and their associated control inputs, such methods are too slow and computationally expensive. This paper investigates a Reinforcement Learning (RL) based approach for real-time optimal control as a potential solution. Using the Proximal Policy Optimization (PPO) method, a complex policy is developed by training a neural network controller to solve an optimal control problem. One hundred simulations are shown demonstrating the performance of this trained agent in controlling a 2000kg spacecraft during a transfer between two distant retrograde orbits from varying initial positions. [View Full Paper]

[*] Graduate Student, Department of Aeronautics and Astronautics, Massachusetts Institute of Technology, Cambridge, Massachusetts 02139, USA. E-mail: dmmiller@mit.edu. Student Member AIAA.
[†] Charles Stark Draper Assistant Professor, Department of Aeronautics and Astronautics, Massachusetts Institute of Technology, Cambridge, Massachusetts 02139, USA. E-mail: linaresr@mit.edu. Senior Member AIAA.

AAS 19-566

COLLISION PREDICTION WITHIN A CUBESAT SWARM USING MACHINE LEARNING

Patrick Doran[*] and Navid Nakhjiri[†]

This paper presents an algorithm of predicting collisions in a swarm of small satellites in orbit. The paper studies a case of eight CubeSats in a relaxed-formation flying in low Earth orbits. Various supervised machine learning methods based on classification, neural network, and regression trees are trained from hundreds of training sets made from simulations to predict the collision in the swarm. The trained algorithms are used to predict the time of possible collision based on the current configuration of the satellite in their orbits.
[View Full Paper]

[*] Undergraduate Student, Aerospace Engineering, Cal Poly Pomona, 3801 W Temple Ave., Pomona, California 91768, USA.
[†] Assistant Professor, Aerospace Engineering, Cal Poly Pomona, 3801 W Temple Ave., Pomona, California 91768, USA.

AAS 19-573

TRAINING SET DATA OPTIMIZATION FOR ARTIFICIAL NEURAL NETWORKS FOR ORBITAL STATE SPACE TRAJECTORY PREDICTIONS

Zachary A. Reinke* and Jennifer S. Hudson†

Demand on earth orbiting object surveillance systems is increasing as more equipment is put into orbit. These systems rely on predictive techniques to periodically track objects. The demand on these systems may be reduced if object trajectories could be predicted farther into the future. Using an artificial neural network (ANN), new prediction models and techniques could be developed to increase prediction time and replace existing methods. The goal of this research is to develop techniques that analyze orbital state trajectory data to develop low density training sets used for training ANN applied to trajectory predictions. These methods use multi-variable statistics to analyze data energy content providing the ANN with low density, feature-rich, training data. [View Full Paper]

* Graduate Student, Mechanical and Aerospace Engineering, Western Michigan University, 1901W. Michigan Ave., Kalamazoo, Michigan 49008-5343, USA.
† Associate Professor, Mechanical and Aerospace Engineering, Western Michigan University, 1901 W. Michigan Ave., Kalamazoo, Michigan 49008-5343, USA.

ASTEROID AND NON-EARTH ORBITING MISSIONS

Session Chairs:

Session 6: Donghoon Kim, Mississippi State University

Session 18: Mar Vaquero, Jet Propulsion Laboratory

AAS 19-234

ON THE DESIGN OF MULTIPLE-REVOLUTION SOLAR GRAVITY DRIVEN ORBITAL TRANSFERS AROUND MARS

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

Multiple spacecraft can transfer to Mars on a single mission using current launch vehicle and electric propulsion technology. Solar gravity can be employed to deploy the multiple spacecraft in drastically different orbits around Mars. The design of such transfers requires an efficient way to model the transfers' dynamics. Previous research demonstrated how artificial neural networks can be designed to accurately capture the dynamics. The emphasis of this work is this architecture's usage to enable the rapid design of solar perturbed transfers around Mars. First, the methodology is developed to identify transfer scenarios with up to four revolutions around Mars, with or without maneuvers at an intermediate periareion. This methodology is applied to identify transfers to one of the Martian moons, or to identify transfers that go to both Martian moons on a single transfer trajectory. Second, it is demonstrated how the artificial neural networks can be utilized to efficiently asses the effect of incorrect maneuvers on the identified transfers. Finally, it is demonstrated how the developed methodology can be generalized for other transfers, and thus how it can be used to provide an understanding of solar gravity driven transfers around Mars, for a large section of the possible phase space. [View Full Paper]

* Graduate Research Assistant, University of Colorado, Boulder, Colorado 80309, USA.
† A. Richard Seebass Endowed Professor, University of Colorado, Boulder, Colorado 80309, USA.
‡ Chief Technology Officer, Advanced Space, Boulder, Colorado 80301, USA.

DEPLOYMENT ANALYSIS AND TRAJECTORY RECONSTRUCTION OF MINERVA-II ROVERS ON ASTEROID RYUGU

Stefaan Van wal,[*] Kent Yoshikawa[†] and Yuichi Tsuda[‡]

The Japanese Hayabusa2 asteroid sample return mission deployed the two small MINERVA-II-1A/B rovers to the surface of asteroid Ryugu in September 2018. An overview of the rover deployment analysis and landing site selection, which was subject to various mission constraints, is provided in this paper. During the deployment, the Hayabusa2 spacecraft obtained images using its three navigation cameras. These images are analyzed using control point matching to identify moving bright and dark spots. By combining the rectified positions of these spots, three object tracks can be observed. A basic understanding of the rover release mechanism enabled classifying the two rovers and their cover to the respective tracks. Initial results on the trajectories reconstruction of these tracks suggest that one rover flew a nominal trajectory while the other was ejected in a somewhat perturbed direction. The cover is seen impacting the surface at roughly 30 cm/s and rebounds with a relatively high energetic restitution of 0.6 to 0.8. Further analysis will narrow down the descent trajectory of the two rovers and provide a more precise estimate of the cover's rebound on the asteroid surface. [View Full Paper]

[*] Aerospace Project Research Associate, Department of Space Flight Systems, Japan Aerospace Exploration Agency, 3-1-1 Yoshinodai, Chuo-ku, Sagamihara, Kanagawa 252-5210 Japan.
[†] Japan Aerospace Exploration Agency, 3-1-1 Yoshinodai, Chuo-ku, Sagamihara, Kanagawa 252-5210 Japan.
[‡] Japan Aerospace Exploration Agency, 3-1-1 Yoshinodai, Chuo-ku, Sagamihara, Kanagawa 252-5210 Japan.

AAS 19-244

SWARM OPTIMIZATION OF LUNAR TRANSFERS FROM EARTH ORBIT WITH RADIATION DOSE CONSTRAINTS

Justin R. Mansell,[*] Samantha Dickmann[†] and David A. Spencer[‡]

Due to the frequent launches of primary satellites into geosynchronous transfer orbits, lunar transfer from an initial geosynchronous transfer orbit represents an attractive option for secondary payloads with lunar mission objectives. The development of advanced launch vehicle upper stages with low boil off rates and restartable engines further enhances the potential of geosynchronous transfer orbits to serve as starting points for lunar transfers. Lunar trajectory design from arbitrarily oriented Earth orbits involves complex tradeoffs that can be successfully addressed with particle swarm optimization. An important mission design consideration is radiation dose, since coasting in a geosynchronous transfer orbit involves repeated passes through the Van Allen radiation belts. In this investigation, a mixture density neural network is trained on the state-of-the-art radiation environment models to provide a surrogate model capable of making probabilistic estimates of radiation dosage. The network is combined with the particle swarm method to optimize the coasting and transfer arcs of a lunar trajectory. The end-to-end design of a trajectory from geosynchronous transfer orbit into a specified lunar orbit is demonstrated by modeling the optimized trajectory in a high-fidelity orbit propagator.

[View Full Paper]

[*] Graduate Student, School of Aeronautics and Astronautics, Purdue University, 701 W. Stadium Ave, West Lafayette, Indiana 47907, USA.
[†] Undergraduate Student, School of Aeronautics and Astronautics, Purdue University, 701W. Stadium Ave, West Lafayette, Indiana 47907, USA.
[‡] Associate Professor, School of Aeronautics and Astronautics, Purdue University, 701 W. Stadium Ave, West Lafayette, Indiana 47907, USA.

AAS 19-253

INITIAL ORBIT DETERMINATION ABOUT SMALL BODIES USING FLASH LIDAR AND RIGID TRANSFORM INVARIANTS

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

This paper proposes a novel approach based on the registration of 3D point clouds acquired by means of a LIDAR instrument to perform initial orbit determination in the vicinity of a small body. Specifically, the proposed methods provide position, velocity and standard gravitational parameter estimates along with their consistent uncertainties. Besides the knowledge of the instrument inertial pointing, no a-priori information is required for the filter to function. Initial results featuring a point-mass gravity model and normally distributed Iterated Closest Point registration errors demonstrate the ability of the filter to quickly characterize the orbit of the spacecraft of interest, yielding a suitable state estimate and state covariance that can be provided to a sequential filter for subsequent navigation, that can be used as-is as a-priori navigation solutions, or used to detect impending impacts with the orbited body. [View Full Paper]

[*] PhD Candidate, Aerospace Engineering Sciences Department, University of Colorado, Boulder, Colorado 80309, USA.

[†] Assistant Professor, Aerospace Engineering Sciences Department, University of Colorado, Boulder, Colorado 80309, USA. AIAA Senior Member.

MULTILAYER CLUSTERED SAMPLING TECHNIQUE (MLCS) FOR NEAR-EARTH ASTEROID IMPACT HAZARD ASSESSMENT*

Javier Roa† and Davide Farnocchia‡

Because of planetary encounters, the motion of near-Earth asteroids is chaotic and small differences in the initial conditions tend to diverge exponentially. Linear approximations for propagating orbital uncertainties can lead to inaccurate estimates of the probability of an Earth collision. We present a novel fully nonlinear strategy for estimating the probability of an asteroid impact using sequential Monte Carlo layers. The method first explores a low-resolution layer to locate potentially relevant regions. Then, we conduct localized searches on deeper layers with higher resolution. The method retains the accuracy of brute-force Monte Carlo sampling while reducing the computational cost by only sampling relevant regions. [View Full Paper]

† Navigation Engineer, Solar System Dynamics Group. Jet Propulsion Laboratory, California Institute of Technology, 4800 Oak Grove Drive, Pasadena, California 91109-8099, USA. javier.roa@jpl.nasa.gov.
‡ Navigation Engineer, Solar System Dynamics Group. Jet Propulsion Laboratory, California Institute of Technology, 4800 Oak Grove Drive, Pasadena, California 91109-8099, USA.

AAS 19-269

SCIENCE ORBIT DESIGN WITH FROZEN BETA ANGLE: THEORY AND APPLICATION TO PSYCHE MISSION

Kenshiro Oguri,[*] Gregory Lantoine,[†] Bill Hart[‡] and Jay W. McMahon[§]

Beta angle, an angle formed by the sunlight and a spacecraft orbital plane, is an important parameter for science orbit design at primitive bodies. This angle defines lighting conditions and eclipse occurrences, and is then used for science observation planning. Not only is this parameter perturbed by the irregular gravity field of the body, it varies along with the body's motion around the Sun. Investigating evolution of the beta angle is therefore critical for science orbit design. This paper presents beta frozen solutions under the J2-perturbed dynamics using the averaged Lagrange Planetary Equations, and extends them to initially-frozen solutions by relaxing the frozen condition in order to enable more flexible mission design. The analytical work is applied to science orbit design of the Psyche mission, a recently selected mission of the NASA's Discovery Program.

[View Full Paper]

[*] Ph.D. Student, Graduate Research Assistant, Colorado Center for Astrodynamics Research, Department of Aerospace Engineering Sciences, UCB, Boulder, Colorado 80309, USA.
[†] Mission Design Engineer, Outer Planet Mission Analysis Group, Jet Propulsion Laboratory, California Institute of Technology, Pasadena, California 91109, USA.
[‡] Systems Engineer, Jet Propulsion Laboratory, California Institute of Technology, Pasadena, California 91109, USA.
[§] Assistant Professor, Colorado Center for Astrodynamics Research, Department of Aerospace Engineering Sciences, UCB, Boulder, Colorado 80309, USA.

AAS 19-339

CURVILINEAR SURFACE-BASED GRAVITY MODEL FOR EVOLUTIONARY TRAJECTORY OPTIMIZATION AROUND BENNU

J. M. Pearl,[*] D. Hinckley,[*] W. F. Louisos[†] and D. L. Hitt[‡]

Missions to small bodies often require a mapping phase during which low altitude operations are required. These low altitude trajectories need to fulfill competing objectives such as: camera surface coverage, camera viewing angle, propellant usage, and safety from impact. The high-dimensional optimization space lends itself to population-based optimization techniques. These methods however, require a large number of trajectories to be integrated, and thus require an accurate gravity model that is quick to evaluate. In the present work, a quadrature-based surface gravity model is developed for use in a differential evolution trajectory optimization routine. Recommendations are made regarding the required number of quadrature points and the order of the quadrature for the problem at hand. [View Full Paper]

[*] Graduate Student, Department of Mechanical Engineering, University of Vermont, Burlington, Vermont 05405, USA.

[†] Senior Lecturer of Mechanical Engineering, Department of Mechanical Engineering, University of Vermont, Burlington, Vermont 05405, USA.

[‡] Professor of Mechanical Engineering, Department of Mechanical Engineering, University of Vermont, Burlington, Vermont 05405, USA.

GRAVITATIONAL CAPTURE AT SATURN WITH LOW-THRUST ASSISTANCE

E. Fantino,[*] J. Peláez,[†] R. Flores[‡] and V. Raposo-Pulido[§]

Orbit insertion at Saturn requires a large manoeuver with chemical thrusters to compensate for the velocity difference between the spacecraft and the planet. The impact that this has on the propellant budget is severe. This paper discusses an alternative strategy: after a gravity assist with Jupiter, an electrical motor with an ad hoc thrusting law reshapes the orbit and minimizes the hyperbolic excess speed at Saturn, thus facilitating the capture. The control law algorithm, as well as the dynamical and technological aspects are presented and discussed. [View Full Paper]

[*] Assistant Professor, Aerospace Engineering Department, Khalifa University of Science and Technology, P.O. Box 127788 Abu Dhabi, United Arab Emirates. Research Fellow, Space Dynamics Group, School of Aeronautical and Space Engineering, Technical University of Madrid, Plaza Cardenal Cisneros 3, 28040 Madrid, Spain.
[†] Professor, Space Dynamics Group, School of Aeronautical and Space Engineering, Technical University of Madrid, Plaza Cardenal Cisneros 3, 28040 Madrid, Spain. Visiting Scholar, Aerospace Engineering Department, Khalifa University of Science and Technology, P.O. Box 127788 Abu Dhabi, United Arab Emirates.
[‡] Associate Professor, International Center for Numerical Methods in Engineering, Campus Norte UPC, Gran Capitán s/n, 08034 Barcelona, Spain.
[§] PhD Candidate, Space Dynamics Group, School of Aeronautical and Space Engineering, Technical University of Madrid, Plaza Cardenal Cisneros 3, 28040 Madrid, Spain.

AAS 19-385

LAGRANGE – MISSION ANALYSIS FOR THE EUROPEAN SPACE AGENCY'S SPACE WEATHER MISSION TO THE SUN-EARTH LIBRATION POINT L5

Florian Renk,[*] Michael Khan[*] and Mehdi Scoubeau[*]

In the frame of the European Space Agency's Space Situational Awareness Programme a space weather mission is currently being studied. For this mission the satellite is envisioned to be placed at the Sun-Earth Libration Point L5. Observations from the L5 point allow to see Sun activities not yet visible from Earth with the potential to provide earlier warnings of solar activity by 4.5 days. A spacecraft in orbit about L5 can also monitor the entire space between the Sun and the Earth, allowing mid-course tracking of coronal mass ejections and predictions of their arrival times at Earth.

For a transfer towards the triangular Sun-Earth L5 point the S/C must trail the Earth by 60°. To avoid a too long transfer phase the results for 14 and 26 months transfer will be presented. A maximum performance launch on an Ariane 6.2 launch vehicle from Kourou yields to a low declination interplanetary departure trajectory, leading to a strong seasonal variation of the out-of-plane component with respect to the ecliptic plane, causing a strong variation in the required transfer DeltaV when inserting directly into the Sun-Earth L5 point.

In order to enable the use of a fixed antenna used for communication the variation of the orbital S/C position about the nominal S/C-Sun-Earth angle of 60 Deg is expected to be not more than ~0.3 degree. Mission analysis results shows that significant gains in ΔV savings can be achieved already when allowing a variation as small as 0.25 degree about the nominal value in line with the requirement for the antenna pointing limitation.

Initial analysis shows that no station-keeping manoeuvres will be required for typical spacecraft disturbances due to the stability of the Sun-Earth L5 orbital environment. [View Full Paper]

[*] European Space Agency (ESA), Robert-Bosch-Straße 5, 64293 Darmstadt, Germany.

TRAJECTORY DESIGN FOR LUMIO CUBESAT IN THE CISLUNAR SPACE

Diogene A. Dei Tos* and Francesco Topputo†

The Lunar Meteoroid Impacts Observer, or LUMIO, is a CubeSat mission concept awarded ex-aequo winner of ESA's SysNova Competition "Lunar CubeSats for Exploration" that shall observe, quantify, and characterize the meteoroid impacts by detecting their flashes on the lunar farside. After a study at the ESA/ESTEC concurrent design facility, LUMIO is now under consideration for future implementation by the Agency. In this paper, we propose the implementation of a sophisticated orbit design, concept of operations, and station-keeping strategy: LUMIO is placed on a quasi-halo orbit about Earth–Moon L_2. The baseline solution is presented with evidence to support the orbit design. [View Full Paper]

* Postdoctoral Fellow, Department of Aerospace Science and Technology, Politecnico di Milano, Milan, Italy.
† Assistant Professor, Department of Aerospace Science and Technology, Politecnico di Milano, Milan, Italy.

AAS 19-411

MASCOT: FLIGHT DYNAMICS ACTIVITIES IN SUPPORT OF AN ASTEROID LANDING MISSION

Elisabet Canalias,* Laurence Lorda,* Thierry Martin,* Romain Garmier,† Aurélie Moussi,* Tra-Mi Ho‡ and Jens Biele§

MASCOT, the Mobile Asteroid Surface SCOuT, is a small lander jointly developed by the German and French space agencies, that has travelled on board of the JAXA S/C Hayabusa2 for over 3 years to the C-type asteroid called Ryugu. The goal of MASCOT lander was to perform in situ measurements on the surface of the asteroid thanks to its four scientific payloads, participating in a substantial way in the overall scientific return of Hayabusa2 mission. The French contribution to MASCOT includes the batteries, together with the power control and distribution unit, the antennae for communication with the mother S/C, the provision of the infrared spectrometer MicrOmega developed by the Space Astrophysics Institute (IAS, Orsay, France), and finally, the flight dynamics support to all the technical, scientific and operational teams involved in MASCOT mission. The objective of the present paper is to provide an overview of all the flight dynamics activities performed for MASCOT project: from the early mission analysis studies and the preparation of the operational tools, up to the landing site selection process that took place in summer 2018 (after the arrival of Hayabusa2 to the vicinity of Ryugu), and the currently on-going activities of restitution of the real descent trajectory and attitude of MASCOT. [View Full Paper]

* CNES, 18 Av. Edouard Belin, 31400 Toulouse (France).
† CS-SI, Communication & System, Rue brindejonc des moulinais, 31500 Toulouse (France).
‡ DLR, Robert-Hooke-Strasse 7, 28359 Bremen (Germany).
§ DLR, Linder Höhe, 51147 Köln (Germany).

AAS 19-412

A NEW ENVIRONMENT TO SIMULATE THE DYNAMICS IN THE CLOSE PROXIMITY OF RUBBLE-PILE ASTEROIDS

Fabio Ferrari[*†]

This paper presents a new environment to simulate close-proximity dynamics around rubble-pile asteroids. The code provides methods for modeling the asteroid's gravity field and surface through granular dynamics. It implements state-of-the-art techniques to model both gravity and contact interaction between particles: 1) mutual gravity as either direct N2 or Barnes-Hut GPU-parallel octree and 2) contact dynamics with a soft-body (force-based, smooth dynamics), hard-body (constraint-based, non-smooth dynamics), or hybrid (constraint-based with compliance and damping) approach. A very relevant feature of the code is its ability to handle complex-shaped rigid bodies and their full 6D motion. Examples of spacecraft close-proximity scenarios and their numerical simulations are shown. [View Full Paper]

[*] Jet Propulsion Laboratory, California Institute of Technology, Pasadena, California 91109, USA.
[†] Department of Aerospace Science and Technology, Politecnico di Milano, Milan, Italy, 20156.

AAS 19-415

SRP-BASED ORBIT CONTROL WITH APPLICATION TO ORBIT STATIONKEEPING AT SMALL BODIES

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

With appropriate control algorithms, solar radiation pressure (SRP) can be effectively exploited as a source of orbit control force around asteroids. A concept of SRP-based orbit control utilizes the SRP acceleration for controlling spacecraft orbits by *active* attitude changes, for which the authors recently developed an optimal control law with an asteroid landing scenario. In contrast to a hypothetical spacecraft assumed in the landing scenario, common spacecrafts usually have lower area-to-mass ratios as well as attitude constraints such as a constraint on the maximum pitch angle of spacecraft solar panels against the sunlight. Extending the concept to such common spacecrafts requires careful design of a feedback control gain associated with the control law. This paper introduces a state-dependent feedback gain for the control law and demonstrates the controller's capability with two scenarios inspired by the OSIRIS-REx science planning: 1) orbit stationkeeping at science orbits and 2) orbit transfer in-between. [View Full Paper]

* Ph.D. Student, Graduate Research Assistant, Colorado Center for Astrodynamics Research, Department of Aerospace Engineering Sciences, UCB, Boulder, Colorado 80309, USA.

† Assistant Professor, Colorado Center for Astrodynamics Research, Department of Aerospace Engineering Sciences, UCB, Boulder, Colorado 80309, USA.

AAS 19-427

ASTEROID MANIPULATION WITH ACTIVE BOULDER REMOVAL

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

A linearized small angular velocity and inertia tensor deviation model is developed and examined for close-to-principal-axis rotators. The model is used to reduce precession of a rotating body by aligning the inertia tensor with the angular velocity deviation. The model is also applied to launching boulders off of asteroid surfaces, proving that the principal-axis rotator characteristic can be kept while removing material off the surface. A disruption case is presented, showing how the model can be used to maximize the precession outcome of boulder launch. [View Full Paper]

[*] Ph.D. Candidate, Smead Department of Aerospace Engineering Sciences, University of Colorado, Boulder Colorado 80309, USA.

[†] Assistant Professor, Smead Department of Aerospace Engineering Sciences, University of Colorado, Boulder Colorado 80309, USA.

APPROACH TO EXPLORING INTERSTELLAR OBJECTS AND LONG-PERIOD COMETS

Julie C. Castillo-Rogez,* Damon Landau,†
Soon-Jo Chung‡ and Karen Meech§

This paper aims to identify the best approaches for exploring planetary bodies with very long orbital periods, i.e., bodies that approach Earth only once in a lifetime. This includes long-period comets (LPCs), and the newly discovered classes of Manx comets and interstellar objects (ISOs). Long-period comets are high scientific value targets, as indicated in the current Planetary Science Decadal Survey. Interstellar objects open the fascinating possibility to sample exoplanetary systems. Manxes hold the key to resolving long-time questions about the early history of our solar system. Specific strategies need to be implemented in order to approach bodies whose orbital properties are at the same time extreme and unpredictable. As ground-based telescope capabilities are greatly improving, it will soon become possible to detect LPCs more than ten years before they reach perihelion. On the other hand, the non- or weakly active Manx comets and ISOs require reactive exploration strategies. All of these bodies offer many challenges for close proximity observations that can be addressed by the deployment of multi-spacecraft architectures. We describe several concepts that leverage the many advantages offered by distributed sensors, fractionated payload, and various mother-daughter configurations to achieve high impact science within the reach of low-cost missions. [View Full Paper]

* Research Scientist, Jet Propulsion Laboratory, California Institute of Technology, Pasadena, California 91109, USA. E-mail: Julie.C.Castillo@jpl.nasa.gov.
† Systems Engineer, Jet Propulsion Laboratory, California Institute of Technology, Pasadena, California 91109, USA. E-mail: Damon.Landau@jpl.nasa.gov.
‡ Professor of Aerospace and Jet Propulsion Lab Research Scientist, California Institute of Technology, Pasadena, California 91125, USA. E-mail: sjchung@caltech.edu.
§ Astronomer, Institute for Astronomy, University of Hawaii, Honolulu, Hawaii 96822, USA.
E-mail: meech@ifa.hawaii.edu.

THE EFFECT OF A SHIFTED ORIGIN ON THE OSCULATING ORBITAL ELEMENTS OF A TERMINATOR ORBIT

Shota Takahashi[*] and Daniel J. Scheeres[†]

In asteroid exploration missions, orbiting about the target body can enhance mission flexibility and science return. However, the dynamics of a spacecraft are in general strongly perturbed by the solar radiation pressure (SRP). It has been shown that the secular dynamics of an SRP perturbed two-body problem has a closed-form solution, and specifically gives us the conditions for a frozen orbit. As there is an offset between the orbit and mass centers, due to SRP, the actual motion deviates from the solution of the secular dynamics. What causes this discrepancy is a short-period variation over one orbit period. In this research, we introduce an arbitrary offset along the Sun-asteroid line and investigate the short-period oscillations of orbital elements defined about the offset. The optimal offset is analytically formulated based on the short-period analysis of angular momentum vector. With the offset, we further discuss two ways to better define the initial conditions for a frozen terminator orbit. It is demonstrated that we can suppress the wobbling of such an orbit by applying a simple modification to the conventional frozen terminator orbit conditions. [View Full Paper]

[*] Doctoral Student, Ann & H.J. Smead Department of Aerospace Engineering Sciences, University of Colorado Boulder, 429 UCB, Boulder, Colorado 80305-0429, USA.
[†] University of Colorado Distinguished Professor, Ann & H.J. Smead Department of Aerospace Engineering Sciences, University of Colorado Boulder, 429 UCB, Boulder, Colorado 80305-0429 USA.

AAS 19-509

MODELING IMAGING UNCERTAINTY FOR OSIRIS-REX'S ASTEROID APPROACH OBSERVATIONS

Kristofer Drozd,[*] Roberto Furfaro,[†] Diane Lambert,[‡] John N. Kidd Jr.,[‡] W. V. Boynton,[§] D. S. Lauretta,[**] H. L. Enos[††] and the OSIRIS-REx Team

This paper outlines and solves the problem of imaging asteroid (101955) Bennu in the presence of spacecraft state perturbation during OSIRIS-REx's approach trajectory. The problem is that the area a mosaic must cover changes size as the spacecraft state is perturbed. We developed and applied a method for determining how much to over-image the area around Bennu to satisfy specific observation requirements. We also implemented machine learning classification techniques to explore their utility at predicting mosaic coverage for future OSIRIS-REx observations. [View Full Paper]

[*] Graduate Student, Systems and Industrial Engineering, University of Arizona, 1127 E. Roger Way, Tucson, Arizona 85721, USA.
[†] Professor, Department of Systems and Industrial Engineering, Department of Aerospace and Mechanical Engineering, University of Arizona, 1127 E. Roger Way, Tucson, Arizona 85721, USA.
[‡] Senior Science Operations Planning Engineer, University of Arizona, 1415 N. Sixth Ave, Tucson, Arizona 85705, USA.
[§] Mission Instrument Scientist, University of Arizona, 1415 N. Sixth Ave, Tucson, Arizona 85705, USA.
[**] Mission Principal Investigator, University of Arizona, 1415 N. Sixth Ave, Tucson, Arizona 85705, USA.
[††] Deputy Principal Investigator, University of Arizona, 1415 N. Sixth Ave, Tucson, Arizona 85705, USA.

EXPECTED ACCURACY OF DENSITY RECOVERY USING SATELLITE SWARM GRAVITY MEASUREMENTS

William Ledbetter,[*] Rohan Sood[†] and Jeffrey Stuart[‡]

Asteroids are of particular interest in the modern space industry due to their potential for advancing knowledge about the origins of the solar system. Identifying and characterizing asteroids with sustainable resources for future space exploration is critical. Additionally, limited knowledge of near-Earth asteroids' physical characteristics such as shape, density, gravity field, and composition pose a challenge to any manned exploration. A stochastic gradient method from the field of deep learning is applied to the problem of asteroid density recovery, with implications for target selection and mining. The algorithm outperforms the predicted observability, and is minimally affected by noisy measurements. [View Full Paper]

[*] Ph.D. Student, Astrodynamics and Space Research Laboratory, Department of Aerospace Engineering and Mechanics, The University of Alabama, Tuscaloosa, Alabama 35487, USA. E-mail: wgledbetter@crimson.ua.edu.

[†] Assistant Professor, Astrodynamics and Space Research Laboratory, Department of Aerospace Engineering and Mechanics, The University of Alabama, Tuscaloosa, Alabama 35487, USA. E-mail: rsood@eng.ua.edu.

[‡] Research Technologist, Jet Propulsion Laboratory, California Institute of Technology, MS 301-121, 4800 Oak Grove Dr., Pasadena, California 91109, USA. E-mail: jeffrey.r.stuart@jpl.nasa.gov.

BALLISTIC MOON-MOON TRANSFERS IN THE CISLUNAR RESTRICTED FOUR-BODY PROBLEM

Anthony L. Genova,[*] Brian D. Kaplinger[†] and David W. Dunham[‡]

This paper investigates the continuity of several families of transfer trajectories using ballistic lunar capture. Ballistic capture trajectories are of interest for spacecraft with low-thrust propulsion or those otherwise unable to enter lunar orbit from a traditional lunar transfer orbit. A continuation model is used to map two-body problem candidate solutions into trajectories satisfying the dynamics of the Sun-Earth-Moon (SEM) restricted four-body problem. The change of each family of candidate solutions with SEM angle of the initial lunar flyby is expected to impact the ability to claim existence of a solution across a wide range of initial TLI epochs. [View Full Paper]

[*] Trajectory Design Lead, Mission Design Division, NASA Ames Research Center, Moffett Field, California 94035, USA.
[†] Deputy Director, Aldrin Space Institute, Florida Institute of Technology, 150 W. University Blvd., Melbourne, Florida 32901, USA.
[‡] Chief Mission Design Engineer, KinetX, Inc., 7913 Kara Ct., Greenbelt, Maryland 20770, USA.

ORBITAL DEBRIS AND SPACE ENVIRONMENT

Session Chairs:

Session 9: Simone D'Amico, Stanford University

CONJUNCTION ASSESSMENT AND RISK MITIGATION AUTOMATION (CARMA)

Mark A. Vincent*

The Conjunction Assessment and Risk Mitigation Automation (CARMA) process at the Jet Propulsion Laboratory is explained, along with a report on its progress to date. Current and future CARMA research topics are included. The former includes a comparison of two different methods (Eigenvalue and Cholesky) to decompose the covariance matrix in order to set up Monte Carlo analyses to calculate the Probability of Collision. Future pursuits include a Predictive Maneuver Trade Space tool. Its purpose and outline of its implementation is presented. [View Full Paper]

* Senior Principal System Engineer, Raytheon, Mailing address: 2810 Colby Drive, Boulder, Colorado 80305, USA.

AAS 19-268

MASS ESTIMATION THROUGH FUSION OF ASTROMETRIC AND PHOTOMETRIC DATA WITH APPLICATIONS TO ORBITAL DEBRIS CHARACTERIZATION*

Matthew Richardson,† Tom Kelecy,‡ Jason Stauch,§ Charles J. Wetterer and Channing Chow††**

A formulation is presented for estimating the mass of a space object by fusing astrometric and photometric data. One practical application of this method is orbital debris characterization. Typically, astrometric measurements (e.g. right-ascension, declination, range, range-rate) are used to estimate the object's orbit plus physical characteristics such as area-to-mass ratio. Processing photometric data (e.g. visual magnitudes) aids in estimating the object's attitude as well as gives insight into its spectral features such as albedo-area. By fusing astrometric and photometric data types (i.e. processing both simultaneously within a single filter), it is possible to disentangle intrinsic properties using derived products such as the albedo-area and area-to-mass ratio to ultimately deduce the mass of the object. Two case studies are presented: (1) a 3-axis stabilized satellite with a low area-to-mass ratio and (2) a high area-to-mass ratio debris object. The unscented Schmidt-Kalman filter (USKF) is used as the estimation engine to allow for the consideration of non-estimable parameters during data fusion. In both use cases, the filter is able to accurately converge on the true mass of the given space object with low uncertainty. This will facilitate understanding of debris objects when characterizing such objects with quantifiable uncertainty. Observability of the state parameters was examined and shown, when relevant, to be a good indicator of when mass, size and attitude can be estimated to very low uncertainty. [View Full Paper]

* DISTRIBUTION STATEMENT A: Approval for public release: distribution unlimited.

† Astrodynamicist, L3 Applied Defense Solutions, 10807 New Allegiance Drive, Suite 150, Colorado Springs, Colorado 80921, USA.

‡ Senior Scientist, L3 Applied Defense Solutions, 10807 New Allegiance Drive, Suite 150, Colorado Springs, Colorado 80921, USA.

§ Aerospace Research Engineer, L3 Applied Defense Solutions, 10807 New Allegiance Drive, Suite 150, Colorado Springs, Colorado 80921, USA.

** Senior Scientist, Pacific Defense Solutions, LLC, 535 Lipoa Parkway, #101, Kihei, Hawaii 96753, USA.

†† Senior Scientist, Pacific Defense Solutions, LLC, 535 Lipoa Parkway, #101, Kihei, Hawaii 96753, USA.

INTERPOLATION AND INTEGRATION OF PHASE SPACE DENSITY FOR ESTIMATION OF FRAGMENTATION CLOUD DISTRIBUTION

Stefan Frey,* Camilla Colombo† and Stijn Lemmens‡

To calculate the effects of on-orbit fragmentations on current or future space missions, accurate estimates of the fragment density and its time evolution are required. Current operational tools estimate the risks involved through representative objects. Such tools, however, cannot accurately estimate the fragment density at any point in space and time. Rather, they directly calculate the number of close approaches from the representative objects. As such, they require a large number of Monte Carlo (MC) simulations to accurately find the collision risk over a large domain. Instead, the continuity equation can be applied to model the fragment density as a continuum, and propagate it forward in time. To model the evolution in any orbital region, the continuum can be propagated semi-analytically along its characteristics. The difficulty arises in estimating the density in between the cloud of samples.

Here, the underlying density distribution is estimated by fitting a Gaussian Mixture Model (GMM) to the characteristics. An example of a break-up in three dimensions is given. It is shown that the model can accurately be fitted at different snapshots after the fragmentation, even with a low number of sample points. Given an analytical expression of the density enables the subsequent integration of the collision risk at any point in the phase space. [View Full Paper]

* PhD Student, Dept. of Aerospace Science and Technology, Politecnico di Milano, Via La Masa, 34, 20156 Milano, Italy.

† Associate Professor, Dept. of Aerospace Science and Technology, Politecnico di Milano, Via La Masa, 34, 20156 Milano, Italy.

‡ Space Debris Analyst, Space Debris Office, ESA/ESOC, Robert-Bosch-Strasse 5, 64293 Darmstadt, Germany.

AAS 19-409

A DENSITY-BASED APPROACH TO THE PROPAGATION OF RE-ENTRY UNCERTAINTIES

Mirko Trisolini* and Camilla Colombo†

The proposed study aims at implementing a density-based approach for the propagation of uncertainties in the initial conditions and parameters for the analysis and prediction of spacecraft re-entries. Using the continuity equation together with the re-entry dynamics, the joint probability distribution function of the uncertainties is propagated and the final uncertainties in the re-entry corridor, impact location, and casualty area are quantified. The paper considers uncertainties in the initial conditions at re-entry and in the ballistic coefficient of the satellite for different types of re-entry scenarios, studying the effects that such uncertainties have on the impact location and entry corridor. [View Full Paper]

* PostDoctoral Researcher, Dipartimento di Scienze e Tecnologie Aerospaziali, Politecnico di Milano, Via La Masa 34, 20156 Milano MI, Italy. AIAA Member.

† PhD, Associate Professor, Dipartimento di Scienze e Tecnologie Aerospaziali, Politecnico di Milano, Via La Masa 34, 20156 Milano MI, Italy. AIAA Member.

AAS 19-438

DATA-DRIVEN INVESTIGATION OF THERMOSPHERIC VARIATIONS

Piyush M. Mehta* and Richard Linares†

This paper presents a methodology for data-driven investigation of thermospheric variations that uses modal decomposition to extract high-dimensional basis for the correlated variation of the neutral thermospheric species and temperature. The extracted basis functions are combined with CHAMP and GRACE mass density measurements using a non-linear least squares solver. We demonstrate the methodology using the MSIS model to derive high-dimensional basis functions. We use the methodology to investigate oxygen-to-helium transition through variations of the individual species as the relative abundance of the two species have a direct impact on drag and orbit prediction through gas-surface interactions and mass density. In addition, we attempt to characterize and quantify the temperature and lower boundary effects that cause the difference between model and measurements. [View Full Paper]

* Assistant Professor, Department of Mechanical and Aerospace Engineering, Statler College of Engineering and Mineral Resources, West Virginia University, Morgantown, West Virginia 26506-6106, USA.
† Charles Stark Draper Assistant Professor, Department of Aeronautics and Astronautics, Massachusetts Institute of Technology, Cambridge, Massachusetts 02139, USA.

AAS 19-439

ON DERIVING SELF-CONSISTENT, HIGH-ACCURACY MASS DENSITY MEASUREMENTS

Piyush M. Mehta*

High-accuracy thermospheric mass density estimates derived from measurements of orbital drag on-board the CHAMP and GRACE satellites have been the workhorse of upper atmospheric research for close to two decades. These estimates use drag coefficients (C_D) computed with neutral species composition from some empirical model that provides global estimates by combining diffusive equilibrium profiles with lower boundary number density estimates that can contain errors. The derived density estimates are then used to generate corrections to the model(s) used to derive them, making the process circular in nature. Recent work on self-consistent calibration of empirical models provide insight into the errors in lower boundary estimates and temperature profiles. This paper investigates its impact on the process of deriving density estimates from measurements of acceleration onboard satellites by recomputing density estimates using composition and temperature from the assimilated state. Results indicate that the current process of estimating density may be inconsistent as the recomputed density estimates can have significant differences from the original density estimates, especially during solar minimum conditions, because of significant redistribution of lighter species like helium and inaccurate models.
[View Full Paper]

* Assistant Professor, Department of Mechanical and Aerospace Engineering, Statler College of Engineering and Mineral Resources, West Virginia University, Morgantown, West Virginia 26506-6106, USA.

AAS 19-465

ROBUSTNESS OF TARGETING REGIONS OF CHAOS IN THE GNSS REGIME

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

This paper investigates the sensitivity of resonant and chaotic orbital dynamics proximate to GNSS satellites. These regions are caused by luni-solar resonances and are defined by the semimajor axis, eccentricity, and inclination. However, they are dependent on the position of the sun, moon, and other orbital parameters. This work will describe how sensitive the system is based on the different orbital parameters in an effort to determine the feasibility of targeting these regions for debris disposal. [View Full Paper]

[*] PhD Student, Ann and H.J. Smead Department of Aerospace Engineering Sciences, University of Colorado, Boulder Colorado 80309, USA.
[†] A. Richard Seabass Chair Professor, Ann and H.J. Smead Department of Aerospace Engineering Sciences, University of Colorado, Boulder Colorado 80309, USA.

AAS 19-480

LARGE CONSTELLATION DE-ORBITING WITH LOW-THRUST PROPULSION

S. Huang,* C. Colombo,† E. M. Alessi‡ and Z. Hou§

This paper deals with the propulsive phase of de-orbiting phase for coplanar satellites in large constellations. The design is conducted via two layers: the first layer is to design a time-optimal deorbiting trajectory for a single satellite; the second layer is to find the optimal de-orbit timing for each satellite to start the de-orbiting in order to minimize the total transfer time as well as the inner constellation collision risk. For the first layer, two de-orbit strategies are considered: the first strategy aims at lowering the perigee; the second strategy aims at reaching a natural de-orbiting corridor. For each strategy, the quasi time-optimal steering law is developed, and the secular variations of the orbital elements are derived by using the averaging technique. For the second layer, the inner constellation collision risk is evaluated by miss distance; the optimal de-orbit timings are found for different de-orbit sequences by using a multi-objective optimization technique.

[View Full Paper]

* PhD Student, Department of Aerospace Science and Technology, Politecnico di Milano, Via La Masa 34, 20156 Milano MI, Italy. E-mail: simeng.huang@polimi.it.
† Associate Professor, Department of Aerospace Science and Technology, Politecnico di Milano, Via La Masa 34, 20156 Milano MI, Italy. E-mail: camilla.colombo@polimi.it.
‡ Researcher, Instituto di Fisica Applicata Nello Carrara, Consiglio Nazionale delle Ricerche, Via Madonna del Piano 10, 50019 Sesto Fiorentino (FI), Italy. E-mail: em.alessi@ifac.cnr.it.
§ Post-Doctoral, Division of Information Science and Technology, Graduate School at Shenzhen, Tsinghua University, Nanshan, Shenzhen, China, 518058. E-mail: hzl1334123@163.com.

KOOPMAN OPERATOR THEORY FOR THERMOSPHERIC DENSITY MODELING

Richard Linares,[*] Piyush M. Mehta,[†] Humberto C. Godinez[‡] and David Gondelach[§]

Low-Earth orbiting (LEO) satellites are heavily influenced by atmospheric drag, which is very difficult to model accurately. This paper demonstrates the Koopman Operator (KO)-theory applied to the TIE-GCM model. The goal of this work is to use a physics-based atmospheric density model for obtaining a Reduced-Order Model (ROM) for density forecasting. It is shown that Koopman/Extended Dynamic Model Decomposition (DMD) approach can reduce propagation error while using fewer modes as compared to the DMD approach which assumes a linear model. Additionally, as Kp, a geomagnetic activity index, goes up, the uncertainty in the DMD model can be as large as 30%, but less than 10% for this initial KO-based model. This result provides optimism for the proposed solution to density modeling, but further improvements are achievable. [View Full Paper]

[*] Charles Stark Draper Assistant Professor, Department of Aeronautics and Astronautics, Massachusetts Institute of Technology, Cambridge, Massachusetts 02139, USA. E-mail: linaresr@mit.edu.

[†] Assistant Professor, Department of Mechanical and Aerospace Engineering, Statler College of Engineering and Mineral Resources, West Virginia University, Morgantown, West Virginia 26506-6106, USA.

[‡] Applied Mathematics Group, Los Alamos National Laboratory, New Mexico 87545. USA.
E-mail: hgodinez@lanl.gov.

[§] Postdoctoral Associate, Department of Aeronautics and Astronautics, Massachusetts Institute of Technology, Cambridge, Massachusetts 02139, USA. E-mail: dgondela@mit.edu.

RESIDENT SPACE OBJECT PROPER ORBITAL ELEMENTS

Aaron J. Rosengren,[*] Davide Amato,[†] Claudio Bombardelli[‡] and Moriba Jah[§]

Proper elements are obtained as a result of the elimination of short and long periodic perturbations from their instantaneous, osculating counterparts, and therefore represent a kind of average characteristic of motion. Projected into proper element space, asteroids tend to cluster around special values of the orbital elements leading to their unique classification into dynamical families. Proper elements thus appear to have application to a number of underpinning areas of SSA, including the dynamical taxonomy of resident space objects and the association of debris from breakup into its parent satellite. Here, we work out a preliminary theory of proper orbital elements in the circumterrestrial context. We recover a classical solution of Cook (1966) on frozen orbits and adopted it in a semi-analytical computation of geocentric proper eccentricity. These quasi integrals were found to be nearly constant on decadal timescales for high altitude LEO satellites.

[View Full Paper]

[*] Department of Aerospace and Mechanical Engineering, University of Arizona, Tucson, Arizona 85721, USA.
[†] Department of Aerospace and Mechanical Engineering, University of Arizona, Tucson, Arizona 85721, USA.
[‡] Technical University of Madrid (UPM), Madrid, 28040, Spain.
[§] Department of Aerospace Engineering and Engineering Mechanics, University of Texas, Austin, Texas 78712, USA.

ATMOSPHERIC RE-ENTRY AND SATELLITE CONSTELLATIONS

Session Chairs:

Session 11: Kamesh Subbarao, University of Texas at Arlington

The following paper was not available for publication:

AAS 19-499 Paper Withdrawn

AAS 19-212

INVESTIGATION OF DIRECT FORCE CONTROL FOR PLANETARY AEROCAPTURE AT NEPTUNE

Rohan G. Deshmukh,[*] Soumyo Dutta[†] and David A. Spencer[‡]

In this work, a direct force control numerical predictor-corrector guidance architecture is developed to enable Neptune aerocapture using flight-heritage blunt body aeroshells. A linear aerodynamics model is formulated for a Mars Science Laboratory-derived aeroshell. The application of calculus of variations shows that the optimal angle of attack and side-slip angle control laws are bang-bang. A closed-loop numerical predictor-corrector direct force control guidance algorithm is developed and numerically simulated using the Program to Optimize Simulated Trajectories II. The Monte Carlo simulated trajectories are demonstrated to be robust to the modeled dispersions in aerodynamics, atmospheric density, and entry state. An aerocapture technology trade study demonstrates that blunt body direct force control aerocapture enables similar performance as slender body bank angle control but halves the peak g-loading. [View Full Paper]

[*] Graduate Research Assistant, School of Aeronautics and Astronautics, Purdue University, 480 W Stadium Ave., West Lafayette, Indiana 47907, USA.

[†] Aerospace Engineer, Atmospheric Flight and Entry Systems Branch, NASA Langley Research Center, 1 Nasa Dr., Hampton, Virginia 23666, USA.

[‡] Associate Professor, School of Aeronautics and Astronautics, Purdue University, 480 W Stadium Ave., West Lafayette, Indiana 47907, USA.

AAS 19-301

AUTOPILOT FOR NEAR-SPACE HYPERSONIC VEHICLE CONTROLLED BY AERODYNAMIC LIFT AND DIVERT THRUSTERS WITH OFF-CENTERED SEEKER WINDOW

Penglei Zhao,[*] Wanchun Chen[†] and Wenbin Yu[‡]

This paper presents the design of an autopilot of the near-space hypersonic vehicle that is controlled by aerodynamic lift and divert thrusters and has an off-centered seeker window. To ensure that the seeker can reliably track maneuvering target, the vehicle has to adjust the attitude to achieve a favorable seeker viewing orientation. However, the attitude adjustment also affects the trajectory because it changes the angle of attack. Therefore, in order to decouple the control of the attitude and trajectory, a command allocation algorithm following the aerodynamic-divert-first principle is proposed to coordinate the divert and attitude control systems such that the acceleration command can be closely tracked while the constraint on the field-of-view (FOV) is satisfied. Thereafter, a high-order sliding mode controller using nonlinear dynamic sliding manifold technique is designed for the control of the attitude control system, and a pulse-width pulse-frequency modulator is designed for the control of the divert control system. Simulation results show that the autopilot is able to effectively control the vehicle to intercept the target with small miss distance while satisfying the FOV constraint, and robust to uncertainties.
[View Full Paper]

[*] Ph.D. Candidate, School of Astronautics, Beihang University, Beijing, 100083, China.
[†] Professor, School of Astronautics, Beihang University, Beijing, 100083, China.
[‡] Associate professor, School of Astronautics, Beihang University, Beijing, 100083, China. Corresponding author. E-mail address: yuwenbin_buaa@163.com.

AAS 19-402

DESIGN OF A RESILIENT RIDESHARE-BASED SMALL SATELLITE CONSTELLATION USING A GENETIC ALGORITHM

Katherine E. Mott[*] and Jonathan T. Black[†]

Responsive and resilient space-based systems are needed to satisfy changing mission requirements and react to unforeseen challenges. This paper studies the ability of a constellation constructed from commercial-off-the-shelf parts and launched using rideshare to provide imaging coverage over a small region in the event of a disaster, such as an outbreak of wildfires. A genetic algorithm and model-based systems engineering techniques are used to evaluate rideshare constellations in both the nominal case and the case in which some satellites have failed. Novel methods for determining reachability between two orbits and for determining revisit metrics for degraded constellations are presented. [View Full Paper]

[*] Graduate Student, Crofton Dept. of Aerospace and Ocean Engineering, Virginia Tech, Blacksburg, Virginia 24060, USA. AIAA Member.

[†] Professor, Crofton Dept. of Aerospace and Ocean Engineering, Virginia Tech, Blacksburg, Virginia 24060, USA. AIAA Associate Fellow.

AAS 19-431

DIFFERENTIAL LIFT AND DRAG CONSTELLATION CONTROL USING TRIMMED ATTITUDE

Andrew Harris* and Hanspeter Schaub†

Spacecraft operating in Low Earth Orbit can leverage atmospheric forces to reduce fuel consumption and improve robustness to hardware failure. This work aims to extend prior work in differential-drag formation flight to the constellation domain through the use of linearized relative orbital elements. A gas-surface interaction model is evaluated for multiple possible surface material properties, demonstrating the potential feasibility of lift forces for actuating specially-designed spacecraft. Small variations to attitude about a reference attitude–referred to as "trimmed attitude" in this work–are considered as the control input, allowing for the construction of a system that is affine in control. A Lyapunov-based control strategy is derived and demonstrated in simulation to validate the lift sensitivity matrix. [View Full Paper]

* Research Assistant, Smead Department of Aerospace Engineering Sciences, Graduate Student, University of Colorado Boulder, Boulder, Colorado 80309 USA.
† Glenn L. Murphy Chair of Engineering, Smead Department of Aerospace Engineering Sciences, University of Colorado, 431 UCB, Colorado Center for Astrodynamics Research, Boulder, Colorado 80309-0431. AAS Fellow.

PARKING ORBIT SELECTION FOR MARS AEROCAPTURE-ENTRY SYSTEMS

Evan J. Zinner* **and Zachary R. Putnam†**

This study explores parking orbit selection for an aerocapture-entry system at Mars and assesses the impact on vehicle design. For dual-heat-pulse trajectories, there is a tradeoff between energy dissipated during aerocapture and energy dissipated during entry. This study explores that tradeoff and the effects on the total entry system mass. The effect of non-virgin thermal protection system during entry, descent, and landing is considered. The analysis finds that the mass from the thermal protection system does not vary significantly depending on orbit selection. The larger driver of entry system mass is the propellant needed to stabilize the parking orbit. This leads to longer period parking orbits having less entry system mass. [View Full Paper]

* Graduate Student, Department of Aerospace Engineering, University of Illinois at Urbana-Champaign, 107 S. Wright St., Urbana, Illinois 61801, USA.

† Assistant Professor, Department of Aerospace Engineering, University of Illinois at Urbana-Champaign, 107 S. Wright St., Urbana, Illinois 61801, USA.

AAS 19-468

STOCHASTIC REACHABILITY ANALYSIS FOR THE HYPERSONIC RE-ENTRY PROBLEM

Amit Jain,[*] Damien Guého,[†] Puneet Singla[‡] and Maruthi Akella[§]

In this paper, a computationally efficient approach is presented to enable onboard computation of reachability sets for the hypersonic re-entry problem. The main idea is to consider the bounded control variables as random variables and represent the reachability sets as the level sets of the state probability density function. A main advantage of such an approach is that it provides not only the boundary of the reachability set but it also characterizes the probability distribution of state variable due to variation in control input. The computation of state density function due to variation in control input at each time is made tractable by computing desired order statistical moments of state density function at each time. Conjugate Unscented Transform (CUT) algorithm is used to compute the moment generating function. Finally, a prototype model of the hypersonic re-entry problem is considered to show the efficacy and utility of the proposed ideas. [View Full Paper]

[*] Graduate Student, Department of Aerospace Engineering, The Pennsylvania State University, State College, Pennsylvania 16802, USA. E-mail: axj307@psu.edu.

[†] Graduate Student, Department of Aerospace Engineering, The Pennsylvania State University, State College, Pennsylvania 16802, USA. E-mail: djg76@psu.edu.

[‡] Associate Professor, Department of Aerospace Engineering, The Pennsylvania State University, State College, Pennsylvania 16802, USA. E-mail: psingla@psu.edu. AIAA Associate Fellow, AAS Fellow.

[§] Professor, Department of Aerospace Engineering, The University of Texas, Austin, Texas 78712.
E-mail: makella@mail.utexas.edu. AIAA Associate Fellow, AAS Fellow.

AAS 19-491

NEURAL NETWORK TRAINED CONTROLLER FOR ATMOSPHERIC ENTRY IN MARS MISSIONS

Hao Wang,* Dillon Martin† and Tarek Elgohary‡

We present a new method to design the controller of Mars capsule atmospheric entry using neural networks. Compared to Apollo controller as a baseline, the simulation of neural network controller reproduces the classical Apollo results over a variation of initial conditions, e.g. initial position. This leads to the potential of achieving landing accuracy requirements of future manned Mars missions. The data from Apollo re-entry simulation in Earth model is used for neural networks training. The neural network controller for Earth reentry is evaluated with Apollo real data. It is then adapted for the Mars environment and achieves the desired landing accuracy for a Mars capsule. The results show significant promise in using that approach for future Mars missions. [View Full Paper]

* PhD Student, Department of Mechanical and Aerospace Engineering, University of Central Florida, Orlando, Florida 32826, USA.
† Undergraduate Student, Department of Mechanical and Aerospace Engineering, University of Central Florida, Orlando, Florida 32826, USA.
‡ Assistant Professor, Department of Mechanical and Aerospace Engineering, University of Central Florida, Orlando, Florida 32826, USA.

OPTIMAL GUIDANCE FOR MARS AEROCAPTURE MANEUVER

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

The paper presents the study of an aerocapture maneuver to insert a Crew Transfer Vehicle from an Earth-Mars cycling orbit into a Low Mars Orbit. Details about the optimal control method used to guide the spacecraft through the planet's atmosphere are presented. The Hermite-Simpson direct collocation method is used to optimize the trajectory by targeting the atmospheric exit conditions necessary for the vehicle to reach the desired post-aerocapture orbit apoapsis and to minimize the Δv necessary to circularize the post aerocapture orbit. Additional constraints are imposed on the trajectory such that the maximum load factor, dynamic pressure and heating rate tolerable by the crew and vehicle are not exceeded. [View Full Paper]

* Graduate Research Assistant, Aerospace Engineering, Florida Institute of Technology, Melbourne, Florida 32901, USA.

† Assistant Professor, Aerospace Engineering, Florida Institute of Technology, Melbourne, Florida 32901, USA.

‡ Deputy Director, Aldrin Space Institute, Florida Institute of Technology, Melbourne, Florida 32901, USA.

§ Aerospace Engineer, Atmospheric Flight and Entry Systems Branch, NASA Langley Research Center, Hampton, Virginia 23681, USA.

DYNAMICAL SYSTEMS THEORY

Session Chairs:

Session 14: Diane Davis, a.i. solutions, Inc.

AAS 19-266

DESIGNING LOW-THRUST ENABLED TRAJECTORIES FOR A HELIOPHYSICS SMALLSAT MISSION TO SUN-EARTH L5

Ian Elliott,* Christopher Sullivan Jr.,* Natasha Bosanac,† Jeffrey R. Stuart‡ and Farah Alibay§

A small satellite deployed to Sun-Earth L5 could serve as a low-cost platform to observe solar phenomena such as coronal mass ejections. However, the small satellite platform introduces significant challenges into the trajectory design process via limited thrusting capabilities, power and operational constraints, and fixed deployment conditions. To address these challenges, a strategy employing dynamical systems theory is used to design a low-thrust-enabled trajectory for a small satellite to reach the Sun-Earth L5 region. This procedure is demonstrated for a small satellite that launches as a secondary payload with a larger spacecraft destined for a Sun-Earth L2 halo orbit. [View Full Paper]

* Graduate Research Assistant, Smead Department of Aerospace Engineering Sciences, University of Colorado Boulder, Boulder Colorado 80309, USA.
† Assistant Professor, Colorado Center for Astrodynamics Research, Smead Department of Aerospace Engineering Sciences, University of Colorado Boulder, Boulder Colorado 80309, USA.
‡ Mission Design and Navigation Systems Engineer, Jet Propulsion Laboratory, California Institute of Technology, Pasadena, California 91109, USA.
§ Systems Engineer, Jet Propulsion Laboratory, California Institute of Technology, Pasadena, California 91109, USA.

AAS 19-267

EXPLORING THE LOW-THRUST TRAJECTORY DESIGN SPACE FOR SMALLSAT MISSIONS TO THE SUN-EARTH TRIANGULAR EQUILIBRIUM POINTS

Christopher J. Sullivan,* Ian Elliott,* Natasha Bosanac,† Farah Alibay‡ and Jeffrey R. Stuart§

With the increasing availability of upcoming rideshare opportunities, low-thrust-enabled small satellites could be leveraged as a platform for targeted heliophysics investigations conducted from the Sun-Earth L4 or L5 regions. In the early stages of mission concept development for small satellites, understanding the trajectory trade space and the influence of the spacecraft hardware configuration and scientific objectives is crucial. Fundamental dynamical structures within the Sun-Earth system are examined and used to extract insight into the properties of the trajectory design space for low-thrust-enabled small satellites to visit Sun-Earth L4 or L5 from several fixed deployment conditions.

[View Full Paper]

* Graduate Research Assistant, Smead Department of Aerospace Engineering Sciences, University of Colorado Boulder, Boulder, Colorado 80309, USA.
† Assistant Professor, Colorado Center for Astrodynamics Research, Smead Department of Aerospace Engineering Sciences, University of Colorado Boulder, Boulder, Colorado 80309, USA.
‡ Systems Engineer, Jet Propulsion Laboratory, California Institute of Technology, Pasadena, California 91109, USA.
§ Mission Design and Navigation Systems Engineer, Jet Propulsion Laboratory, California Institute of Technology, Pasadena, California 91109, USA.

AAS 19-280

TRANSIT AND CAPTURE IN THE PLANAR THREE-BODY PROBLEM LEVERAGING LOW-THRUST DYNAMICAL STRUCTURES

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

Path planning in the circular restricted 3-body problem (CR3BP) is frequently guided by the forbidden regions and manifold arcs. However, when low-thrust is employed to modify the spacecraft trajectory, these dynamical structures pulsate with the varying Hamiltonian value. In a combined CR3BP, low-thrust (CR3BPLT) model, an additional low-thrust Hamiltonian is available that remains constant along low-thrust arcs. Accordingly, the analogous low-thrust forbidden regions and manifolds are static and are useful guides for low-thrust trajectory design. Strategies leveraging these structures and other insights from the CR3BP-LT are explored to construct transit and capture itineraries.

[View Full Paper]

* Ph.D. Student, School of Aeronautics and Astronautics, Purdue University, West Lafayette, Indiana 47907, USA. E-mail: cox50@purdue.edu.

† Hsu Lo Distinguished Professor of Aeronautics and Astronautics, School of Aeronautics and Astronautics, Purdue University, West Lafayette, Indiana 47907, USA. E-mail: howell@purdue.edu.

‡ Senior Fellow, NASA Goddard Space Flight Center, Greenbelt, Maryland 20771, USA. E-mail: david.c.folta@nasa.gov.

ATTITUDE DYNAMICS OF A RIGID BODY IN CIRCULAR ORBIT. RELATIVE EQUILIBRIA AND STABILITY

Jorge L. Zapata,[*] Francisco Crespo,[†] Sebastián Ferrer[‡] and Francisco J. Molero[§]

We address the attitude dynamics of a triaxial rigid body in a circular orbit. This task is done by means of an intermediary model, which is obtained by splitting the Hamiltonian in the form $H = H_0 + H_1$, where H_0 is required to be a nondegenerate integrable 1-DOF Hamiltonian system. A numerical study is presented for the intermediary comparing the dynamics of the new model with the full system (MacCullagh's truncation), for the cases Sun-asteroid and Earth-spacecraft. Both scenarios show a competitive performance of the H_0 model. This model defines a Poisson flow based on the use of the invariants defining a $S^2_M \times S^2_M$ reduced space. We analyze the coupling between the orbital mean motion and rotational variables. The key role played by the moments of inertia and the value of the angular momentum is shown in detail. The analysis of the H_0 system shows that under slow rotation regime the classic dynamics of the free rigid body is no longer maintained: bifurcations with changes of stability are displayed for several critical inclinations of the rotational angular momentum plane and for critical orientations of the body frame. Moreover, the evolution of the angular momentum plane is determined by the angle ϕ, which is given by a time dependent harmonic oscillator. [View Full Paper]

[*] Mg, Dpto. Matemática, grupo GISDA, Univ. del Bío-Bío, Collao 1202. Concepción, Chile.
E-mail: jzapata.mat@gmail.com.
[†] Prof. Dpto. Matemática, grupo GISDA, Univ. del Bío-Bío, Collao 1202. Concepción, Chile.
E-mail: fcrespo@ubiobio.cl.
[‡] Prof. Space Dynamics Group, DITEC, Facultad Informática, Univ. de Murcia, Spain. E-mail: sferrer@um.es.
[§] Dr. Space Dynamics Group, DITEC, Facultad Informática, Univ. de Murcia, Spain.
E-mail: javier.moleromadrid@gmail.com.

SPARSE OPTIMAL TRAJECTORY DESIGN IN THREE-BODY PROBLEM

Yuki Kayama,* Mai Bando† and Shinji Hokamoto‡

A structure of the optimal trajectory for minimizing fuel consumption in an unstable dynamical environment such as the three-body problem is not well studied. Recently, it has been found that a sparse solution structure appears in the optimal control of a dynamical system. The concept of sparsity explains the property that the minimum fuel trajectory corresponds to the trajectory which minimizes the total thrusting time. In this paper, we propose a numerical method to obtain the minimum fuel sparse optimal trajectory in the unstable dynamical system. As an example, proposed methods are applied to the transfer in the Sun-Earth system. [View Full Paper]

* Ph.D. Student, Department of Aeronautics and Astronautics, Kyushu University, 744 Motooka, Nishi-ku, Fukuoka, Japan 819- 0395. E-mail: kayama@aero.kyushu-u.ac.jp.
† Associate Professor, Department of Aeronautics and Astronautics, Kyushu University, 744 Motooka, Nishi-ku, Fukuoka, Japan 819- 0395.
‡ Professor, Department of Aeronautics and Astronautics, Kyushu University, 744 Motooka, Nishi-ku, Fukuoka, Japan 819- 0395.

GLOBAL SEARCH OF RESONANT TRANSFERS FOR A EUROPA LANDER TO CLIPPER DATA RELAY*

Damon Landau† and Stefano Campagnola‡

Following its prime mission Europa Clipper becomes a potential asset to relay data from a proposed Europa Lander back to Earth. To this end, we describe an efficient method to globally search for trajectories that repeatedly fly over the same location of Europa. Different families of trajectories emerge with different flyby geometries that satisfy a convoluted set of landing constraints. Here, the landing location and local solar time must match a limited set derived from expected Clipper observations, while providing multiple opportunities to land in a given season. We include estimates for data volume and radiation dose associated with these resonant trajectories. [View Full Paper]

† Mission Formulation Engineer, Project Systems Engineering and Mission Formulation Group, Jet Propulsion Laboratory, California Institute of Technology, Pasadena, California 91109, USA.

‡ Senior Engineer, Outer Planet Mission Analysis Group, Mission Design and Navigation Section, Jet Propulsion Laboratory, California Institute of Technology, Pasadena, California 91109, USA.

AAS 19-372

NEW RESULTS ON MINIMUM-TIME CONTROL OF LINEAR SYSTEMS BETWEEN ARBITRARY STATES WITH APPLICABILITY TO SPACE FLIGHT

Marcello Romano* **and Fabio Curti†**

A new solution method, recently developed by the authors, is presented which is solving for the first time to the best knowledge of the authors the general problem of minimum-time control of a linear time-invariant normal system evolving from an arbitrary initial state to an arbitrary desired final state subjected to cubic-constrained controls (no-rest to no-rest minimum time control problem). The method and its demonstration are here summarized. Furthermore, new solutions found by using that method are illustrated for the double integrator system and the undamped harmonic oscillator system. These models are applicable to several problems encountered in space-flight dynamics.

[View Full Paper]

* Professor, Naval Postgraduate School, Monterey, California 93943, USA.
† Associate Professor, Sapienza University of Rome, 00185 Rome, Italy.

AAS 19-543

FINDING SYMMETRIC HALO ORBITS FRAMED AS A GLOBAL OPTIMIZATION PROBLEM USING MONOTONIC BASIN HOPPING

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

In this work we use the stochastic optimization algorithm Monotonic Basin Hopping to find symmetric halo orbits of a prescribed amplitude in the Sun-Earth and Earth-Moon systems through posing the search as an optimization problem. By minimizing deviations from qualifications that lead to a symmetric halo orbit, such an orbit is found. Stochastic methods are well suited for this problem due to its highly multi-modal nature. Monotonic Basin Hopping is proposed here since it can take advantage of the clustering of sub-optima around an orbit of desired precision by using a zero-mean random distribution for its hop operations; this work uses a Gaussian distribution. The result is a fast means of finding halo orbits of a desired amplitude that are symmetric within a prescribed tolerance. [View Full Paper]

* Ph.D. Student in Mechanical Engineering, University of Vermont, Burlington, Vermont 05405 USA.
† Professor of Mechanical Engineering, University of Vermont, Burlington, Vermont 05405 USA.

SPECIAL SESSION – MARS INSIGHT

Session Chairs:

Session 15: Eric Gustafson, NASA / JPL Caltech

2018 MARS INSIGHT TRAJECTORY RECONSTRUCTION AND PERFORMANCE FROM LAUNCH THROUGH LANDING

Fernando Abilleira,[*] Allen Halsell,[†] Gerhard Kruizinga,[‡] Eugene Bonfiglio,[§] Robert Grover,[**] Min-Kun Chung,[††] Ken Fujii,[‡‡] Eric Gustafson,[§§] Yungsun Hahn,[***] David Jefferson,[†††] Eunice Lau,[‡‡‡] Julim Lee,[§§§] Sarah Elizabeth McCandless,[****] Neil Mottinger,[††††] Jill Seubert,[‡‡‡‡] Evgeniy Sklyanskiy[§§§§] and Mark Wallace[*****]

The InSight mission successfully launched to Mars on an Atlas V 401 launch vehicle from the Western Test Range (WTR) at Vandenberg Air Force Base (VAFB) at 04:05:00 PDT on May 5th, 2018 and landed in the Elysium Planitia Region on November 26th, 2018. Data confirming nominal touchdown was received at 11:52:59 AM PST. This paper summarizes in detail the actual vs. predicted performance of the InSight spacecraft and all associated assets in terms of launch vehicle events, injection performance, DSN performance, cruise performance, and Entry, Descent, and Landing events.

[View Full Paper]

[*] InSight Deputy Mission Manager, E-mail: Fernando.Abilleira@jpl.nasa.gov.
[†] Navigation Team Chief, E-mail: Charles.A.Halsell@jpl.nasa.gov.
[‡] InSight Deputy Navigation Team Chief, E-mail: Gerhard.L.Kruizinga@jpl.nasa.gov.
[§] InSight EDL Systems Engineer, E-mail: Eugene.Bonfiglio@jpl.nasa.gov.
[**] InSight EDL Team Lead, E-mail: Myron.R.Grover@jpl.nasa.gov.
[††] InSight Maneuver Analyst, E-mail: Min-Kun.Chung@jpl.nasa.gov.
[‡‡] InSight Mission Planning Lead, E-mail: Kenneth.K.Fujii@jpl.nasa.gov.
[§§] InSight Orbit Determination Lead, E-mail: Eric.D.Gustafson-133274@jpl.nasa.gov.
[***] InSight Maneuver Analyst, E-mail: Yungsun.Hahn@jpl.nasa.gov.
[†††] InSight Orbit Determination Analyst, E-mail: David.C.Jefferson@jpl.nasa.gov.
[‡‡‡] InSight Orbit Determination Analyst, E-mail: Eunice.L.Lau@jpl.nasa.gov.
[§§§] InSight Orbit Determination Analyst, E-mail: Julim.Lee@jpl.nasa.gov.
[****] InSight Orbit Determination Analyst, E-mail: Sarah.E.McCandless@jpl.nasa.gov.
[††††] InSight Orbit Determination Analyst, E-mail: Neil.Mottinger@jpl.nasa.gov.
[‡‡‡‡] InSight Orbit Determination Analyst, E-mail: Jill.Tombasco@jpl.nasa.gov.
[§§§§] InSight EDL Trajectory Analyst, E-mail: Evgeniy.Sklyanskiy@jpl.nasa.gov.
[*****] InSight Trajectory Lead, E-mail: Mark.S.Wallace@jpl.nasa.gov.
Jet Propulsion Laboratory, California Institute of Technology, Pasadena, California 91109, USA.

AAS 19-209

MARS RECONNAISSANCE ORBITER NAVIGATION STRATEGY FOR SUPPORT OF INSIGHT LANDER'S ENTRY, DESCENT AND LANDING SEQUENCE

Premkumar R. Menon,[*] Sean V. Wagner, David C. Jefferson, Eric J. Graat, Kyong J. Lee, William B. Schulze, Robyn M. Woollands and Kevin E. Criddle[†]

The Mars Reconnaissance Orbiter (MRO) provided primary relay support for the InSight mission's Entry, Descent and Landing (EDL) on November 26, 2018. To position MRO for relay support during InSight EDL, two propulsive maneuvers were performed: the first on August 22, 2018 and the second on October 24, 2018. This paper documents the phasing strategy employed by the MRO Navigation Team to support the InSight EDL sequence. [View Full Paper]

[*] MRO Navigation Team Chief and Corresponding Author; Mailing Address: Jet Propulsion Laboratory, Mail Stop 264-282, 4800 Oak Grove Drive, Pasadena, California 91109, USA.
E-mail address: 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, USA.

INSIGHT ORBIT DETERMINATION[*]

Eric D. Gustafson,[†] C. Allen Halsell,[‡] David Jefferson,[§] Eunice Lau,[§] Julim Lee,[§] Sarah Elizabeth McCandless,[§] Neil Mottinger[§] and Jill Seubert[§]

The InSight mission relied on accurate deep-space navigation for a successful Mars landing on November 26, 2018. In this paper, we discuss the role of the cruise Orbit Determination team, whose responsibilities included determining the spacecraft state, predicting the future trajectory, and quantifying the uncertainty associated with those estimates. In particular, we will focus on spacecraft dynamic modeling, small forces due to attitude control, radiometric tracking data, filter strategies, uncertainty quantification, and responses to unexpected flight situations. We will also provide analysis of reconstructed maneuvers, small forces, and delivery accuracy at Mars arrival. [View Full Paper]

[†] InSight Orbit Determination Lead, Mission Design and Navigation Section, Jet Propulsion Laboratory, California Institute of Technology, 4800 Oak Grove Drive, Pasadena, California 91109, USA.

[‡] InSight Navigation Team Chief, Mission Design and Navigation Section, Jet Propulsion Laboratory, California Institute of Technology, 4800 Oak Grove Drive, Pasadena, California 91109, USA.

[§] InSight Orbit Determination Analyst, Mission Design and Navigation Section, Jet Propulsion Laboratory, California Institute of Technology, 4800 Oak Grove Drive, Pasadena, California 91109, USA.

AAS 19-222

INSIGHT ATTITUDE CONTROL SYSTEM THRUSTER CHARACTERIZATION AND CALIBRATION FOR SUCCESSFUL NAVIGATION TO MARS

Jill Seubert,[*] Eric D. Gustafson,[†] C. Allen Halsell,[‡] Julim Lee[§] and Sarah Elizabeth McCandless[**]

In order for the InSight spacecraft to execute a safe Mars landing, it was crucial that the navigation team accurately predict the trajectory and deliver the spacecraft to the targeted atmospheric entry point. One of the primary challenges faced by the Navigation Team was the accurate reconstruction and prediction of small but frequent velocity changes imparted by the spacecraft's Attitude Control System thrusters. This paper discusses the in-flight thruster calibration campaign, the reconstruction and prediction of accelerations throughout various phases of cruise (including compensating for significant outgassing after launch and attitude transition), and the subsequent impact on atmospheric entry point delivery. [View Full Paper]

[*] Orbit Determination Analyst, Mission Design and Navigation Section, NASA Jet Propulsion Laboratory, California Institute of Technology, 4800 Oak Grove Drive, Pasadena, California 91109, USA.
[†] Orbit Determination Lead, Mission Design and Navigation Section, NASA Jet Propulsion Laboratory, California Institute of Technology, 4800 Oak Grove Drive, Pasadena, California 91109, USA.
[‡] Navigation Team Chief, Mission Design and Navigation Section, NASA Jet Propulsion Laboratory, California Institute of Technology, 4800 Oak Grove Drive, Pasadena, California 91109, USA.
[§] Orbit Determination Analyst, Mission Design and Navigation Section, NASA Jet Propulsion Laboratory, California Institute of Technology, 4800 Oak Grove Drive, Pasadena, California 91109, USA.
[**] Orbit Determination Analyst, Mission Design and Navigation Section, NASA Jet Propulsion Laboratory, California Institute of Technology, 4800 Oak Grove Drive, Pasadena, California 91109, USA.

AAS 19-228

NAVIGATION PERFORMANCE OF THE 2018 INSIGHT MARS LANDER MISSION

Allen Halsell,* Min-Kun Chung,† Eric Gustafson,‡ Yungsun Hahn,§ David Jefferson, Gerhard Kruizinga,†† Eunice Lau,‡‡ Julim Lee,§§ Sarah Elizabeth McCandless,*** Neil Mottinger,††† Jill Seubert,‡‡‡ Evgeniy Sklyanskiy§§§ and Mark Wallace*****

The NASA InSight spacecraft was launched successfully from Vandenberg Air Force Base on an Atlas V-401 launch vehicle on May 5, 2018 and landed on November 26, 2018. Accurate targeting to the atmospheric entry point by the Navigation team achieved by carefully controlling the final entry flight path angle to -12.0 degrees with a tolerance of ±0.21 degrees. This paper will describe how the InSight Navigation team met this difficult task in the presence of frequent unbalanced thrusting for attitude control. The continuous correction for these rotations far exceeded pre-launch expectations and proved a challenge to predict accurately. [View Full Paper]

* InSight Navigation Team Chief, E-mail: Charles.A.Halsell@jpl.nasa.gov.
† InSight Maneuver Analyst, E-mail: E-mail: Min-Kun.Chung@jpl.nasa.gov.
‡ InSight Orbit Determination Lead, E-mail: Eric.D.Gustafson@jpl.nasa.gov.
§ InSight Maneuver Analyst, E-mail: Yungsun.Hahn@jpl.nasa.gov.
** InSight Orbit Determination Analyst, E-mail: David.C.Jefferson@jpl.nasa.gov.
†† InSight Backup Team Chief, E-mail: Gerhard.L.Kruizinga@jpl.nasa.gov.
‡‡ InSight Orbit Determination Analyst, E-mail: Eunice.L.Lau@jpl.nasa.gov.
§§ InSight Orbit Determination Analyst, E-mail: Julim.Lee@jpl.nasa.gov.
*** InSight Orbit Determination Analyst, E-mail: Sarah.E.McCandless@jpl.nasa.gov.
††† InSight Orbit Determination Analyst, E-mail: Neil.A.Mottinger@jpl.nasa.gov.
‡‡‡ InSight Orbit Determination Analyst, E-mail: Jill.Tombasco@jpl.nasa.gov.
§§§ InSight Entry, Descent, and Landing Trajectory Analyst, E-mail: Evgeniy.Sklyanskiy@jpl.nasa.gov.
**** InSight Trajectory Lead, E-mail: Mark.S.Wallace@jpl.nasa.gov.
All authors, Jet Propulsion Laboratory, California Institute of Technology, 4800 Oak Grove Drive, Pasadena, California 91109, USA.

MANEUVER DESIGN OVERVIEW OF THE 2018 INSIGHT MARS LANDER MISSION

Min-Kun Chung,[*] Yungsun Hahn,[†] C. Allen Halsell,[‡]
Sarah Elizabeth McCandless,[§] Evgeniy Sklyanskiy[**] and Mark Wallace[††]

Launched on May 5, 2018, the Interior Exploration using Seismic Investigations, Geodesy, and Heat Transport (InSight) spacecraft landed safely on Mars on November 26, 2018. To deliver the lander accurately to the landing site, six trajectory correction maneuvers (TCMs) were planned along the reference trajectory from Earth launch to Mars entry. For the last two TCMs, there were two corresponding contingency TCMs planned that could be executed in the event that the corresponding nominal one failed. There were also twenty pre-designed menu TCMs available for execution at the time of the last contingency TCM, about 8 hours before the Mars entry, descent, and landing. This navigation paper overviews the maneuver design of each TCM, as well as how each one actually performed during operations. [View Full Paper]

[*] Mission Design Engineer, Mission Design and Navigation Section, Jet Propulsion Laboratory, California Institute of Technology, M/S 264-820, 4800 Oak Grove Drive, Pasadena, California 91109, USA.
[†] Navigation Engineer, Mission Design and Navigation Section, Jet Propulsion Laboratory, California Institute of Technology, M/S 264-820, 4800 Oak Grove Drive, Pasadena, California 91109, USA.
[‡] InSight Navigation Team Chief, Mission Design and Navigation Section, Jet Propulsion Laboratory, California Institute of Technology, M/S 264-820, 4800 Oak Grove Drive, Pasadena, California 91109, USA.
[§] Navigation Engineer, Mission Design and Navigation Section, Jet Propulsion Laboratory, California Institute of Technology, M/S 264-820, 4800 Oak Grove Drive, Pasadena, California 91109, USA.
[**] Mission Design Engineer, Mission Design and Navigation Section, Jet Propulsion Laboratory, California Institute of Technology, M/S 198-326, 4800 Oak Grove Drive, Pasadena, California 91109, USA.
[††] Mission Design Engineer, Mission Design and Navigation Section, Jet Propulsion Laboratory, California Institute of Technology, M/S 264-850, 4800 Oak Grove Drive, Pasadena, California 91109, USA.

MARS RECONNAISSANCE ORBITER MANEUVER PLAN FOR MARS 2020 ENTRY, DESCENT, AND LANDING SUPPORT AND BEYOND

Sean V. Wagner* and Premkumar R. Menon†

The Mars Reconnaissance Orbiter (MRO) spacecraft continues to perform valuable science observations at Mars, provide telecommunication relay for surface assets, and characterize landing sites for future missions. MRO provided primary relay support for the InSight mission during Entry, Descent, and Landing (EDL) on November 26, 2018. This paper discusses the current maneuver plan to support Mars 2020 EDL and maintain MRO's orbit for science operations until 2028. [View Full Paper]

* MRO Maneuver Lead and Corresponding Author, Member of the Mission Design and Navigation Section, Mailing Address: Jet Propulsion Laboratory, Mail Stop 264-282, 4800 Oak Grove Drive, Pasadena, California 91109, USA. E-mail address: Sean.V.Wagner@jpl.nasa.gov; Tel: (818) 393-5972.

† MRO Navigation Team Chief, Member of the Mission Design and Navigation Section, Jet Propulsion Laboratory, California Institute of Technology, Pasadena, California 91109, USA.

AAS 19-264

ATMOSPHERIC IMPACTS ON EDL MANEUVER TARGETING FOR THE INSIGHT MISSION AND UNGUIDED MARS LANDERS[*]

Eugene P. Bonfiglio,[†] Mark Wallace,[‡] Eric Gustafson,[§] Evgeniy Sklyanskiy,[**] Min-Kun Chung[††] and Devin Kipp[‡‡]

Early in operational testing for the InSight mission to Mars, it was discovered that the final maneuver to target the entry-interface point (EIP) was unexpectedly sensitive, in both magnitude and direction, to planned atmosphere model updates that would be based on real-time measurements of the Martian atmosphere by Mars Reconnaissance Orbiter (MRO). Upon investigation, the team realized that the Phoenix mission also discovered this sensitivity during its operational testing. A further investigation identified that maneuver sensitivity to real-time atmosphere updates was a result of the fact that both the EFPA and ground target were being held fixed, constraining the maneuver in a way that forced the entry time to change in order to compensate for changes to the nominal trajectory from updating the atmosphere model. The final maneuver occurs 22 hours prior to entry, at which point it is very expensive to change entry time. The study also revealed that any unguided Mars entry, descent, and landing (EDL) mission would be impacted by this sensitivity if it used real-time atmosphere observations to model the nominal expected atmosphere used for maneuver targeting of the EIP. This paper discusses the results of that investigation and presents a number of mitigations as well as the consequences of ignoring the sensitivity. [View Full Paper]

[†] InSight EDL Systems Engineer, E-mail: Eugene.Bonfiglio@jpl.caltech.edu.
[‡] InSight Trajectory Lead, E-mail: Mark.S.Wallace@jpl.caltech.edu.
[§] InSight Orbit Determination Lead, E-mail: Eric.D.Gustafson-133274@jpl.caltech.edu.
[**] InSight Entry, Descent, and Landing Trajectory Analyst, E-mail: Evgeniy.Sklyanskiy@jpl.caltech.edu.
[††] InSight Maneuver Analyst, E-mail: Min-Kun.Chung@jpl.caltech.edu.
[‡‡] InSight EDL Systems Engineer, E-mail: Devin.Kipp@jpl.caltech.edu.
All authors, Jet Propulsion Laboratory, California Institute of Technology, Pasadena, California 91109, USA.

ORBITERS, CUBESATS, AND RADIO TELESCOPES, OH MY; ENTRY, DESCENT, AND LANDING COMMUNICATIONS FOR THE 2018 INSIGHT MARS LANDER MISSION

Mark S. Wallace,* Daniel Litton,† Tomas Martin-Mur‡ and Sean Wagner§

The Interior Exploration using Seismic Investigations, Geodesy, and Heat Transport (InSight) Mars lander mission was launched on May 5th, 2018 and its November 26, 2018 entry, descent, and landing sequence was observed by no less than five separate assets. The Mars Reconnaissance Orbiter (MRO) in orbit about Mars, the two Mars Cube One (MarCO) probes flying by, and two radio telescopes back on Earth were all used for this critical event communication coverage. These many paths of communication were enabled via the InSight launch/arrival strategy design, MRO orbital phasing selection, and MarCO trajectory design. [View Full Paper]

* Mission Design Engineer, Mission Design and Navigation Section, Jet Propulsion Laboratory, California Institute of Technology, MS 264-820, Pasadena, California 91109, USA.
† Aerospace Engineer, NASA Langley Research Center, MS 489, Hampton, Virginia 23666, USA.
‡ Navigation Engineer, Mission Design and Navigation Section, Jet Propulsion Laboratory, California Institute of Technology, MS 264-820, Pasadena, California 91109, USA.
§ Navigation Engineer, Mission Design and Navigation Section, Jet Propulsion Laboratory, California Institute of Technology, MS 230-205, Pasadena, California 91109, USA.

SPECIAL SESSION – MARS SAMPLE RETURN

Session Chairs:

Session 16: Ryan Woolley, NASA / Caltech JPL

The following papers were not available for publication:

AAS 19-225 Paper Withdrawn

AAS 19-555 Paper Withdrawn

AAS 19-230

MARS SAMPLE RETURN ORBITAL RENDEZVOUS DETECTION METHODS

Robert J. Haw[*] and Eric D. Gustafson[†]

Navigation trades while in pursuit of a rendezvous with a sample capsule in orbit around Mars are described. The rendezvous operation is described in terms of far-field and near-field detection. Passive optical detection is compared with active capsule detection using a radio beacon. Passive methods are, to first order, unconstrained by time while a radio beacon link is time-limited. A possible activity to make use of orbiter plume interactions is explored. [View Full Paper]

[*] Navigation Engineer, Mission Design and Navigation, Jet Propulsion Laboratory, California Institute of Technology, 4800 Oak Grove Drive, Pasadena, California 91109, USA.
[†] Navigation engineer, Mission Design and Navigation, Jet Propulsion Laboratory, California Institute of Technology, 4800 Oak Grove Drive, Pasadena, California 91109, USA.

LOW-THRUST TRAJECTORY BACON PLOTS FOR MARS MISSION DESIGN

Ryan C. Woolley,[*] Frank Laipert,[†] Austin K. Nicholas[‡] and Zubin Olikara[§]

The best way to understand a mission design trade space is by creating a good map of all the possibilities, and by knowing how to read it. Bacon plots, which are low-thrust analogs to porkchop plots, give insight into key parameters and sensitivities of possible transfers to Mars (or other destinations). They are mission and parameter specific, and can be created to represent single or multiple legs. This paper outlines the creation process and lessons learned in interpreting the results. An example is given on how bacon plots have been employed for complex mission-level optimization. [View Full Paper]

[*] Mission Design Engineer, Inner Planets Mission Analysis, Jet Propulsion Laboratory, California Institute of Technology, 4800 Oak Grove Drive, Pasadena, California 91109, USA.
[†] Mission Design Engineer, Flight Path Control, Jet Propulsion Laboratory, California Institute of Technology, 4800 Oak Grove Drive, Pasadena, California 91109, USA.
[‡] Systems Engineer, Project Systems Engineering and Formulation, Jet Propulsion Laboratory, California Institute of Technology, 4800 Oak Grove Drive, Pasadena, California 91109, USA.
[§] Mission Design Engineer, Inner Planets Mission Analysis, Jet Propulsion Laboratory, California Institute of Technology, 4800 Oak Grove Drive, Pasadena, California 91109, USA.

HYBRID CHEMICAL-ELECTRIC TRAJECTORIES FOR A MARS SAMPLE RETURN ORBITER

Frank Laipert,[*] Austin Nicholas,[†] Zubin Olikara,[†] Ryan Woolley[†] and Rob Lock[†]

The Earth return orbiter component of a Mars sample return campaign is a high total impulse mission with challenging timeline constraints. These competing demands mean a hybrid chemical-electric propulsion architecture may be needed for a feasible design, with chemical propulsion providing timely impulse and electric propulsion providing high volume impulse. We describe an approach to map out the hybrid trajectory design space and create a database to use in conjunction with a spacecraft design tool, enabling co-optimization of trajectory and spacecraft. This method is applied to both the outbound and inbound legs of a Mars sample return mission concept. [View Full Paper]

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

SIMULTANEOUS OPTIMIZATION OF SPACECRAFT AND TRAJECTORY DESIGN FOR INTERPLANETARY MISSIONS UTILIZING SOLAR ELECTRIC PROPULSION[*]

Austin K. Nicholas,[†] Ryan C. Woolley,[‡]
Alan Didion,[§] Frank Laipert,[**] Zubin Olikara,[††] Ryan Webb[‡‡] and Rob Lock[§§]

A major challenge in formulating interplanetary mission concepts utilizing electric propulsion is the large number of trajectory variables that must be considered (thrust profile, flyby options, launch vehicle delivery), all of which are affected by spacecraft design variables (power, mass, thruster, payload, staging). This is significantly more complex than traditional ballistic/chemical mission design and early concepts are often suboptimal as a result, potentially missing valuable options. This paper presents a novel tool (MORT) for simultaneously optimizing the spacecraft design alongside the trajectory given mission constraints and objectives, including example results relevant to the exploration of Mars.
[View Full Paper]

[†] Systems Engineer, Project Systems Engineering and Formulation.
[‡] Mission Design Engineer, Inner-Planets Mission Analysis.
[§] Systems Engineer, Project Systems Engineering and Formulation.
[**] Mission Design Engineer, Flight Path Control.
[††] Mission Design Engineer, Inner-Planets Mission Analysis.
[‡‡] Systems Engineer, Project Systems Engineering and Formulation.
[§§] Manager, Mars Program Formulation Office.
All Authors: NASA Jet Propulsion Laboratory, California Institute of Technology, 4800 Oak Grove Drive, Pasadena, California 91109, USA.

MISSION ANALYSIS FOR A POTENTIAL MARS SAMPLE RETURN CAMPAIGN IN THE 2020'S[*]

Austin K. Nicholas,[†] Alan Didion,[†] Frank Laipert,[‡]
Zubin Olikara,[§] Ryan C. Woolley,[§] Rob Lock[**] and Jakob Huesing[††]

The Mars 2020 mission, currently under development by NASA, plans to acquire and cache carefully-selected rock and regolith samples from the surface of Mars for potential future return. NASA and ESA are jointly studying options for returning those samples to Earth with missions launching in the 2020s. This paper demonstrates a method for modeling the various campaign elements, synthesizing coordinated campaign timelines, and assuring trajectory feasibility in the presence of many constraints, and finally optimizing towards mission success. Options for complete sample return campaigns in multiple launch and arrival opportunities are explored and compared. [View Full Paper]

[†] Systems Engineer, Project Systems Engineering and Formulation.
[‡] Mission Design Engineer, Flight Path Control.
[§] Mission Design Engineer, Inner-Planets Mission Analysis.
[**] Manager, Mars Program Formulation Office.
(All Above Authors): NASA Jet Propulsion Laboratory, California Institute of Technology, 4800 Oak Grove Drive, Pasadena, California 91109, USA.
[††] Systems Engineer, Systems and Concurrent Engineering Section, European Space Agency, European Space Research & Technology Centre, Keplerlaan 1, 2200AG Noordwijk, The Netherlands.

CHEMICAL AND SOLAR ELECTRIC PROPULSION ORBIT MATCHING FOR MARS SAMPLE RENDEZVOUS[*]

Zubin P. Olikara[†] and Austin K. Nicholas[‡]

A concept for returning samples from the surface of Mars involves rendezvous between an orbiter and a passive sample container in low Mars orbit. This work presents orbit matching maneuver design approaches for chemical and solar electric propulsion (SEP) options. The chemical scheme selects maneuver pairs to setup desired node and phase drifts in tandem. The SEP scheme optimizes the averaged relative dynamics accounting for eclipses, drift due to J_2, and attitude rate constraints. The performance of these approaches is analyzed as a function of orbit inclination and sample container state dispersions. [View Full Paper]

[†] Mission Design and Navigation Section, Jet Propulsion Laboratory, California Institute of Technology, 4800 Oak Grove Drive, Pasadena, California 91109, USA. E-mail: zubin.p.olikara@jpl.nasa.gov.

[‡] Project Systems Engineering & Formulation Section, Jet Propulsion Laboratory, California Institute of Technology, 4800 Oak Grove Drive, Pasadena, California 91109, USA. E-mail: austin.k.nicholas@jpl.nasa.gov.

POTENTIAL CAMPAIGN ARCHITECTURES AND MISSION DESIGN CHALLENGES FOR NEAR-TERM INTERNATIONAL MARS SAMPLE RETURN MISSION CONCEPTS[*]

Robert E. Lock,[†] Austin K. Nicholas,[‡] Sanjay Vijendran,[§] Ryan C. Woolley,[**] Alan Didion,[††] Frank Laipert[‡‡] and Zubin Olikara[§§]

Mars Sample Return (MSR) continues to be a high priority in the planetary science community and a decades-long goal of international planetary exploration programs. Options for architectures and mission concepts are currently under study by NASA and ESA to find potential partnership opportunities to achieve MSR in the 2020s. The major elements of a potential MSR campaign have significant architectural flexibility and mission launch, arrival, and return options. The decision criteria often depend on mission design and functional allocations across many elements. This paper outlines the reference architecture and key trades among the campaign elements. [View Full Paper]

[†] Development Manager, Mars Program Formulation Office, NASA Jet Propulsion Laboratory, California Institute of Technology, 4800 Oak Grove Drive, Pasadena, California 91109, USA. E-mail: robert.e.lock@jpl.caltech.edu.
[‡] Systems Engineer, Project Systems Engineering & Formulation, NASA Jet Propulsion Laboratory, California Institute of Technology.
[§] Mars Sample Return Lead, Human and Robotic Exploration Directorate, European Space Agency - European Space Research and Technology Centre (ESTEC), Keplerlaan 1, 2201 AZ Noordwijk, The Netherlands.
[**] Mission Design Engineer, Inner-Planets Mission Analysis, NASA Jet Propulsion Laboratory, California Institute of Technology.
[††] Systems Engineer, Project Systems Engineering & Formulation, NASA Jet Propulsion Laboratory, California Institute of Technology.
[‡‡] Mission Design Engineer, Flight Path Control, NASA Jet Propulsion Laboratory, California Institute of Technology.
[§§] Navigation Engineer, Inner-Planets Mission Analysis, NASA Jet Propulsion Laboratory, California Institute of Technology.

SPACE SITUATIONAL AWARENESS AND CONJUNCTION ANALYSIS

Session Chairs:

Session 17: Florian Renk, European Space Agency

AAS 19-241

HAYABUSA2 MISSION SOLAR CONJUNCTION TRAJECTORY FOR HOVERING SATELLITE: DESIGN, NAVIGATION AND POST-OPERATION EVALUATION

Stefania Soldini,* Tomohiro Yamaguchi,† Saiki Takanao‡ and Yuichi Tsuda§

Hayabusa2 mission is the ongoing JAXA's sample and return mission to Ryugu asteroid. In late 2018, Ryugu was in superior solar conjunction. Therefore, the Hayabusa2 spacecraft experienced communication blackouts while leaving its hovering position of 20 km from Ryugu. In this article, the design of a safe conjunction trajectory is given in the Hill frame and then verified in the full-body. Two Trajectory Correction Manoeuvres (TCMs) are scheduled before and after the deep conjunction. A linear covariance analysis is shown together with the results of the Monte Carlo analysis to compute the stochastic ΔV at TCMs. Pre-/Post-flight operation data are also compared. [View Full Paper]

* Dr./Project Research Associate, Hayabusa2's Project Team, ISAS/JAXA, Sagamihara, Japan, 252-5210.
† Dr./System Engineer, Hayabusa2's Project Team, ISAS/JAXA, Sagamihara, Japan, 252-5210.
‡ Assoc. Prof./Project Engineer, Hayabusa2's Project Team, ISAS/JAXA, Sagamihara, Japan, 252-5210.
§ Asst. Prof./Project Manager, Hayabusa2's Project Team, ISAS/JAXA, Sagamihara, Japan, 252-5210.

AAS 19-284

ASTEROID RENDEZVOUS MANEUVER DESIGN CONSIDERING UNCERTAINTY

Marc Balducci[*] and Brandon A. Jones[†]

Many current methods of rendezvous maneuver design assume a deterministic system, leaving system uncertainty unquantified, or assume specific posterior distributions. This paper presents the case of a rendezvous while considering the propagated uncertainty of an asteroid and approaching spacecraft. Using the surrogate method of separated representations, uncertainty is efficiently propagated without assuming the posterior distribution and utilized in an optimization under uncertainty algorithm which allows for variations in maneuver components. Two optimization scenarios are presented. The first seeks to maximize the probability of rendezvous while constraining fuel use. A second case considers minimizing fuel use while requiring the probability of rendezvous to remain above a threshold value. Rather than estimating the position state of each object, the presented methodology approximates the distribution of position component differences. This approach improves the accuracy of the surrogate. With this approach, a tractable means of designing a rendezvous maneuver under uncertain conditions is formulated. [View Full Paper]

[*] SSA Researcher, SpaceNav, Boulder, Colorado 80301, USA. E-mail: marco@space-nav.com.
[†] Assistant Professor, The University of Texas at Austin, Department of Aerospace Engineering and Engineering Mechanics, Austin, Texas 78712, USA.

AAS 19-355

TWO-PHASE IMPACT TIME GUIDANCE STRATEGY VIA DUAL-VIRTUAL-TARGET CONCEPT

Yanning Guo,* Pengyu Wang,† Yueyong Lyu‡ and Bong Wie§

This paper presents an analytical, simple guidance design approach to the impact time control problem of constant-speed missiles without any form of time-to-go estimation or numerical iterations. A typical planar engagement scenario of a missile with lateral control acceleration against a stationary target is considered. By employing the differential geometric theory, a circular arc guidance equation (CAGE) of the heading angle is derived, its approximate closed-form solutions are obtained, and a circular predictive guidance (CPG) law is developed. A new dual-virtual-target (DVT) concept is further incorporated into the proposed CPG law to divide the guidance procedure into two phases. The integrated CPG-DVT strategy can guide the missile toward the target in a straight line (with zero lateral control acceleration) during its terminal gliding phase. Numerical simulations are exhibited to validate the effectiveness of the proposed guidance strategy. [View Full Paper]

* Associate Professor, Department of Control Science and Engineering, Harbin Institute of Technology, 150001 Harbin, People's Republic of China. E-mail: guoyn@hit.edu.cn.

† Ph.D. Student, Department of Control Science and Engineering, Harbin Institute of Technology, 150001 Harbin, People's Republic of China. E-mail: wangpy hit@163.com.

‡ Lecturer, Department of Control Science and Engineering, Harbin Institute of Technology, 150001 Harbin, People's Republic of China. E-mail: lvyy@hit.edu.cn.

§ Professor, Department of Aerospace Engineering, Iowa State University, Ames, Iowa 50010-2271, USA. E-mail: bongwie@iastate.edu.

CONTEXT-BASED NON-COMPLIANCE FOR GEO SATELLITE REORBITING

Shiva Iyer,[*] Moriba Jah,[†] Islam Hussein[‡] and Drew McNeely[§]

The Inter-Agency Space Debris Coordination Committee (IADC) established guidelines in 1997 to ensure proper disposal of GEO satellites at the end of their operational lifetimes. This paper analyzes inactive GEO satellites to determine the extent to which they comply with these guidelines. Space object data from USSTRATCOM, JSC Vimpel, the European Space Agency, and Union of Concerned Scientists catalogs are used to obtain the current population of inactive GEO satellites. A consistent data model is developed to capture the parameters of the problem. Context information including country of origin and launch year is used to identify patterns of behavior with regard to compliance.

[View Full Paper]

[*] PhD Student, Department of Aerospace Engineering & Engineering Mechanics, The University of Texas, Austin, Texas 78712, USA.
[†] Associate Professor, Department of Aerospace Engineering & Engineering Mechanics, The University of Texas, Austin, Texas 78712, USA.
[‡] Senior Research Scientist, L3 Applied Defense Solutions, Columbia, Maryland 21044, USA.
[§] PhD Student, Department of Aerospace Engineering & Engineering Mechanics, The University of Texas, Austin, Texas 78712, USA.

AAS 19-437

A PROBABILISTIC APPROACH FOR REACHABILITY SET COMPUTATION FOR EFFICIENT SPACE SITUATIONAL AWARENESS

Zach Hall[*] and Puneet Singla[†]

This focus of this paper is the application of the polynomial approximation method to obtain satellite reachability sets for Space Situational Awareness (SSA) applications. Least squares coefficients for the approximation of the final state solution are calculated in a Jacobian free and computationally tractable manner. The numerical integration method used in the polynomial approximation technique exploits the symmetric structure of the input variable probability density functions (pdf's) to compute the density function for the solution space. The Conjugate Unscented Transformation (CUT) method is utilized for this purpose, and is used to calculate the coefficients with a minimal number of full model propagations. Numerical simulation results are given to validate the approach. [View Full Paper]

[*] Graduate Student, Department of Aerospace Engineering, The Pennsylvania State University, State College, Pennsylvania 16802, USA. E-mail: zyh5059@psu.edu.

[†] Associate Professor, Department of Aerospace Engineering, The Pennsylvania State University, State College, Pennsylvania 16802, USA. E-mail: pxs433@psu.edu. AIAA Associate Fellow, AAS Fellow.

A NEW REPRESENTATION OF UNCERTAINTY FOR COLLISION ASSESSMENT

Emmanuel Delande,[*] Moriba Jah[†] and Brandon Jones[‡]

Assessing collision events is a problem a growing importance in the near-Earth space, where the density of Resident Space Objects (RSOs) is increasing and the actors controlling space assets are growing in number and diversity. In the context of collision assessment, or more generally in the construction of a catalogue of RSOs, it is customary to represent the uncertainty on a RSO state (kinematic state, attitude, etc.) with a random variable and an associated *probability density function* (p.d.f.). However, a probabilistic representation sometimes produces counter-intuitive results, with potentially dangerous implications if they form the basis of a decision-making policy for collision avoidance. We exploit in this paper an alternative representation based on *outer probability measure*s (o.p.m.s) rather than probability distributions, matching more closely the information available on an uncertain system. We show that an o.p.m.-formulation of the RSOs' states leads to more intuitive interpretation of a collision assessment event, and we illustrate this concept on a few simple, simulated scenarios. [View Full Paper]

[*] Research Fellow, Institute for Computational Engineering and Sciences (ICES), The University of Texas at Austin, Austin, Texas 78712, USA.

[†] Associate Professor, Director ICES Computational Astronautical Sciences and Technologies, The University of Texas at Austin, Austin, Texas 78712, USA.

[‡] Assistant Professor, Department of Aerospace Engineering and Engineering Mechanics, The University of Texas at Austin, Austin, Texas 78712, USA.

EARLY COLLISION AND FRAGMENTATION DETECTION OF SPACE OBJECTS WITHOUT ORBIT DETERMINATION

Lyndy E. Axon,* Shahzad Virani† and Marcus J. Holzinger‡

This paper demonstrates that using the hypothesized constraint of the admissible regions, it is possible to determine if a combination of new uncorrelated debris objects have a common origin that also intersects with a known catalog object orbit, thus indicating a likely collision or fragmentation has occurred. Admissible region methods are used to bound the feasible orbit solutions of multiple observations using energy, eccentricity, and radius of periapsis constraints, propagating them to a common epoch in the past, and using gradient-based optimization to find a set of solution states that minimize the Euclidean distance between the observations at that time. If this given one dimensional set of solutions that make up the solution manifold intersects with a known catalog object orbit, then that object is the probabilistic source of the debris objects. This proposed methodology is demonstrated using simulated electro-optical observations from space objects in low Earth and geostationary orbit. [View Full Paper]

* Department of Aerospace Engineering, Georgia Institute of Technology, Atlanta, Georgia 30313, USA.
† Ph.D. Student, Aerospace Engineering Sciences, University of Colorado - Boulder, Boulder, Colorado 80309, USA.
‡ Associate Professor, Aerospace Engineering Sciences, University of Colorado - Boulder, Boulder, Colorado 80309, USA.

AAS 19-506

SPACECRAFT DETECTION AVOIDANCE MANEUVER OPTIMIZATION USING REINFORCEMENT LEARNING

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

Spacecraft maneuvers are planned with operational objectives in mind, usually ranging from making up for orbit perturbations to maneuvering to avoid a possible collision. Though these areas have been researched in depth, little work has been done exploring maneuvers performed to avoid detection by sensors. This paper explores the optimization of detection avoidance maneuvers using reinforcement learning. Numerical transcription is used for comparison purposes, but the open-loop nature of optimal control is not conducive to solving the entirety of the detection avoidance problem. Reinforcement learning produces reliable results for maneuver optimization which will provide a unique alternative for maneuver planning. [View Full Paper]

[*] Graduate Student, Department of Aerospace Engineering, 229 Hammond Building, The Pennsylvania State University, University Park, Pennsylvania 16802, USA.
[†] Professor, Department of Aerospace Engineering, 229 Hammond Building, The Pennsylvania State University, University Park, Pennsylvania 16802, USA.
[‡] Assistant Professor, Aeronautics and Astronautics, 33-328 Massachusetts Institute of Technology, 77 Massachusetts Avenue, Cambridge, Massachusetts 02139, USA.

AN INITIAL ANALYSIS OF AUTOMATING CONJUNCTION ASSESSMENT AND COLLISION AVOIDANCE PLANNING IN SPACE TRAFFIC MANAGEMENT

Jannuel V. Cabrera,[*] Sreeja Nag[†] and David Murakami[‡]

We introduce a framework that automates the process of assessing potential satellite conjunctions in space, and generating collision avoidance maneuvers to support mitigation efforts within a novel space traffic management (STM) architecture. A software implementation of the framework was developed in a MATLAB-STK integrated environment, however, the concept and framework is agnostic to the language or environment. The software pulls from existing catalogs of spaceborne objects and ingests user-defined parameters to produce conjunction data, which could potentially aid collision avoidance planning in the STM architecture. The utility of the software in maneuver planning and exploring a performance-based tradespace of actions is demonstrated using three example cases: one-to-one conjunction, one-versus-four conjunctions, and a near head-on collision. The framework also provides a test-bed for the use of application programming interfaces (APIs) to demonstrate machine-to-machine communication between entities in our proposed STM architecture. Results from this software implementation are expected to aid distributed decision-making among various stakeholders, and inform efficient, autonomous, structured but flexible concept of operations within STM. [View Full Paper]

[*] Graduate Student, Purdue University, NASA Ames Research Center, and Bay Area Environmental Research Institute, Moffett Field, California 94035, USA.

[†] NASA Ames Research Center, and Bay Area Environmental Research Institute, Moffett Field, California 94035, USA.

[‡] NASA Ames Research Center Moffett Field, California 94035, USA.

ASTRODYNAMICS

Session Chairs:

Session 26: Juan Arrieta, Nabla Zero Labs and
Rohan Sood, University of Alabama

The following paper was not available for publication:

AAS 19-215 Paper Withdrawn

LANDING ON EUROPA: KEY CHALLENGES AND ARCHITECTURE CONCEPT

A. K. Zimmer,[*] E. D. Skulsky,[†] A. M. San Martin,[‡] G. Singh,[§] N. Trawny,[**] T. P. Kulkarni[††] and M. E. Greco[‡‡]

With a massive liquid water ocean beneath its icy crust, Europa is one of the Solar System's prime candidates for hosting life. Consequently, there is a strong desire in the scientific community to perform in-situ Europa science through a landed mission. The planned Europa Clipper Mission, which would perform remote science through multiple flybys of Europa, is under development and promises to yield unprecedented insight into this intriguing body. NASA has extended the scope of the potential exploration of Europa beyond the planned Europa Clipper mission and initiated a Pre-Phase A mission concept study of a potential Europa Lander. Jupiter's hostile radiation environment and the lack of information about the moon's terrain at the scale of a lander spacecraft would require significant technology development to overcome the inherent landing challenges. This paper provides an overview of the Europa Lander mission concept and describes the significant challenges associated with landing on Europa, the technologies required to overcome those challenges, and a strategy for Deorbit, Descent, and Landing (DDL).

[View Full Paper]

[*] Systems Engineer, Jet Propulsion Laboratory, California Institute of Technology, 4800 Oak Grove Dr., Pasadena, California 91109, USA.

[†] Guidance and Control Engineer, Jet Propulsion Laboratory, California Institute of Technology, 4800 Oak Grove Dr., Pasadena, California 91109, USA.

[‡] Engineering Fellow, Jet Propulsion Laboratory, California Institute of Technology, 4800 Oak Grove Dr., Pasadena, California 91109, USA.

[§] Guidance and Control Engineer, Jet Propulsion Laboratory, California Institute of Technology, 4800 Oak Grove Dr., Pasadena, California 91109, USA.

[**] Robotics Systems Engineer, Jet Propulsion Laboratory, California Institute of Technology, 4800 Oak Grove Dr., Pasadena, California 91109, USA.

[††] Systems Engineer, Jet Propulsion Laboratory, California Institute of Technology, 4800 Oak Grove Dr., Pasadena, California 91109, USA.

[‡‡] Flight System Engineer, Jet Propulsion Laboratory, California Institute of Technology, 4800 Oak Grove Dr., Pasadena, California 91109, USA.

AAS 19-286

OPTIMAL-FEEDBACK ACCELERATED PICARD ITERATION METHODS AND A FISH-SCALE GROWING METHOD FOR WIDE-RANGING AND MULTIPLE-REVOLUTION PERTURBED LAMBERT'S PROBLEMS

Xuechuan Wang* and Satya N. Atluri†

Wide-ranging and multiple-revolution perturbed Lambert's problems are building blocks for practical missions such as development of cislunar space, interplanetary navigation, orbital rendezvous, etc. However, it is of a great challenge to solve these problems both accurately and efficiently, considering the long transfer time and the complexity of high-fidelity modeling of space environment. For that, a methodology combining Optimal-Feedback Accelerated Picard Iteration methods and Fish-Scale Growing Method is demonstrated. The resulting iterative formulae are explicitly derived and applied to restricted three-body problems and multi-revolution earth rendezvous problem. The examples demonstrate the validity and high efficiency of the proposed methods.

[View Full Paper]

* Research Assistant, Department of Mechanical Engineering, Texas Tech University, Lubbock, Texas 79415, USA.
† Presidential Chair & University Distinguished Professor, Department of Mechanical Engineering, Texas Tech University, Lubbock, Texas 79415, USA.

ENABLING REPEAT-PASS INTERFEROMETRY FROM LOW VENUS ORBIT*

Mark S. Wallace,† Theodore H. Sweetser,‡ Robert J. Haw,§
Eunice Lau** and Scott Hensley††

Repeat-pass interferometry is a powerful technique for determining changes in topography by flying a radar over the terrain two or more times. These overflights must be very close to each other in space. To design and maintain a low Venus orbit that enables this requires the consideration of drag, non-spherical gravity effects, and solar tides. Once the orbit is designed, the spacecraft must be navigated. To do so requires the use of radar-based terrain-relative navigation in addition to the traditional radiometric datatypes. The mission design and navigation to enable repeat-pass interferometry at Venus are described. [View Full Paper]

† Mission Design Engineer, M/S 264-850.
‡ Mission Design Engineer, M/S 301-121.
§ Navigation Engineer, M/S 264-339.
** Navigation Engineer, M/S 264-282.
†† Senior Research Scientist, M/S 300-235.
Jet Propulsion Laboratory, California Institute of Technology, Pasadena, California 91109, USA.

AAS 19-413

JUICE EQUINOX JUPITER TOUR: THE CHALLENGE OF LONG ECLIPSES

Arnaud Boutonnet* **and Gabor Varga†**

JUICE is the next ESA L-class mission towards Jupiter and its Galilean moons. The Jupiter tour is composed of several very different phases requiring a total of 29 flybys before injection in-orbit around Ganymede. The baseline tour in 2022 corresponds to a solstice mission. The backup tour in 2023 leads to an equinox tour and to unacceptable eclipse duration when reusing the baseline tour structure. This paper presents the profound modifications of the tour that were necessary to remain compliant with the spacecraft design constraint. [View Full Paper]

* Senior Mission Analyst, HSO-GFA, ESA-ESOC, Robert-Bosch-Str. 5, D-64293 Darmstadt, Germany.
† Mission Analyst, HSO-GFA, ESA-ESOC, Robert-Bosch-Str. 5, D-64293 Darmstadt, Germany.

VERTICALLY STABLE AND UNSTABLE MANIFOLDS OF PLANAR PERIODIC ORBITS: APPLICATIONS TO SPACECRAFT AND ASTEROID TRAJECTORIES

Kenta Oshima*

This paper highlights natural transport pathways between in-plane and out-of-plane states associated with the vertical instability of planar periodic orbits in the circular restricted three-body problem. Computations of invariant manifolds associated with the vertical instability of planar periodic orbits, "vertically" stable and unstable manifolds, enable quantitative analyses on inclination changes. For spacecraft trajectories, this study uses vertically stable manifolds of planar Lyapunov orbits around the Lagrange points L_1 and L_2 as initial guesses for optimizing transfers from near rectilinear halo orbits to planar distant retrograde orbits (DROs) in the Earth-Moon system. Significant Δv savings as compared with known solutions demonstrate the usefulness of the vertical instability in spacecraft trajectory designs. For asteroid trajectories, this study finds that vertically unstable manifolds associated with planar DROs exhibit long-term stable, highly eccentric, periodic transitions between in-plane and out-of-plane states of the inclination in tens of degrees in the Sun-Jupiter system. It is pointed out that populations of undetected potentially hazardous asteroids of high eccentricity and inclination may reside in Jupiter's vertically unstable DROs, which can intersect the orbits of the terrestrial planets, including the Earth by reducing their inclinations down to near zero via the vertical instability. [View Full Paper]

* Postdoctoral Research Fellow, National Astronomical Observatory of Japan, Tokyo, 181-8588, Japan.
Tel: +819071255894. E-mail: kenta.oshima@nao.ac.jp.

AAS 19-455

CONNECTING RESONANT TRAJECTORIES TO A EUROPA CAPTURE THROUGH LISSAJOUS STAGING ORBITS

Sonia Hernandez,[*] Ricardo L. Restrepo[†] and Rodney L. Anderson[‡]

The current interest in studying the surface of Europa in search of biosignatures demands efficient strategies in mission design to reach this distant world. An affordable strategy is to use a low energy moon tour, which has natural access to the moon via the L_2 gateway. Staging around this libration point allows decoupling the approaching moon tour and the landing trajectory, which enables the option of designing each phase separately. Furthermore, a staging step frees the landing time from the capture phase, adding an additional degree of freedom. Lissajous orbits are the dynamical structures used for these staging orbits. In this paper, the possible ballistic connections between the resonances from the moon tour and Lissajous orbits are studied, including the different geometries that allow for time phasing control. [View Full Paper]

[*] Mission Design Engineer, Jet Propulsion Laboratory, California Institute of Technology, 4800 Oak Grove Drive, Pasadena, California 91109, USA. Corresponding Author: Sonia Hernandez; Tel: (818) 354-0418; E-mail address: Sonia.Hernandez-Doran@jpl.nasa.gov.

[†] Postdoc fellow, Jet Propulsion Laboratory, California Institute of Technology, 4800 Oak Grove Drive, Pasadena, California 91109, USA. E-mail address: ricardo.rpo@utexas.edu.

[‡] Technologist, Jet Propulsion Laboratory, California Institute of Technology, 4800 Oak Grove Drive, Pasadena, California 91109, USA. E-mail address: rodney.anderson@jpl.nasa.gov.

THE STABILITY OF ORBITAL RESONANCES FOR EUROPA QUARANTINE DESIGN: ESCAPE ORBIT CASE*

Brian D. Anderson,† Martin W. Lo‡ and Mar Vaquero§

NASA's planetary protection policies require that spacecraft seek to avoid biologically contaminating Europa. For low-energy missions to Europa, we study the feasibility of placing spacecraft in quarantine orbits. This study sought to define what would be needed for the spacecraft to remain in quarantine orbit around Jupiter long enough to become sterilized by Jupiter's radiation environment. The mutual resonance of the four Galilean moons leads us to predict certain resonances as more stable in the ephemeris model. We verify this through a six-body Galilean System model Poincaré map and propagation in the ephemeris model. [View Full Paper]

† Ph.D. Candidate, Department of Astronautical Engineering, University of Southern California, Los Angeles, California 90089, United States. E-mail: brian.danny.anderson@gmail.com.

‡ Mission Design Engineer, Mission Design and Navigation, Jet Propulsion Laboratory, California Institute of Technology, Pasadena, California 91109, United States. E-mail: martin.w.lo@jpl.caltech.edu.

§ Mission Design Engineer, Mission Design and Navigation, Jet Propulsion Laboratory, California Institute of Technology, Pasadena, California 91109, United States. E-mail: mar.vaquero@jpl.caltech.edu.

AAS 19-484

SURFING IN THE PHASE SPACE OF EARTHS OBLATENESS AND THIRD BODY PERTURBATIONS

Camilla Colombo,[*] Francesca Scala[†] and Ioannis Gkolias[‡]

In this work, we exploit the luni-solar perturbations for the post-mission disposal of satellites in high-altitude orbits. Starting from the double-averaged dynamical system, the representation of the dynamics is reduced to a one degree-of-freedom Hamiltonian, depending on the orbit eccentricity and the perigee orientation in the equatorial frame. An analytical method is proposed for designing the disposal maneuver with the goal to achieve natural re-entry by exploiting the long-term effect of the natural perturbations, enhanced by impulsive maneuvers. The optimal initial conditions to apply the impulsive maneuver, such that a fast re-entry is achieved, are selected via a gradient based method in the phase space. [View Full Paper]

[*] Ph.D., Associate Professor, Department of Aerospace Science and Technology, Politecnico di Milano, Via La Masa 34, 20156, Milano, Italy. E-mail: camilla.colombo@polimi.it.
[†] M.Sc. Space Engineering graduate, Department of Aerospace Science and Technology, Politecnico di Milano, Via La Masa 34, 20156, Milano, Italy. E-mail: francesca.scala@mail.polimi.it.
[‡] Ph.D., Research Fellow, Department of Aerospace Science and Technology, Politecnico di Milano, Via La Masa 34, 20156, Milano, Italy. E-mail: ioannis.gkolias@polimi.it.

PARKING ORBIT DESIGN FOR GENERIC NEAR-EARTH OBJECT FLYBY MISSIONS

Oscar Fuentes-Munoz[*] and Daniel J. Scheeres[†]

Near Earth Objects are promising targets of opportunity for science. We propose and analyze an observation system to be placed in orbit until an interesting NEO is found. Afterwards a probe would be injected to a flyby mission from that orbit. This paper investigates both a suitable parking orbit design and the desired maneuver capabilities for the system. Each proposed parking orbit performance is described statistically based on the NEO database. Discovery conditions arise naturally as design constraints. Lastly, stability concerns of the flyby orbits are covered. [View Full Paper]

[*] Research Assistant, Department of Aerospace Engineering Sciences, University of Colorado Boulder, 429 UCB, Boulder, Colorado 80305-0429, USA.
[†] University of Colorado Distinguished Professor, Department of Aerospace Engineering Sciences, University of Colorado Boulder, 429 UCB, Boulder, Colorado 80305-0429, USA.

A DATA MINING APPROACH TO USING POINCARÉ MAPS IN MULTI-BODY TRAJECTORY DESIGN STRATEGIES

Natasha Bosanac*

Poincaré maps representing two-dimensional data sets are a powerful tool for rapid trajectory design in multi-body systems. However, projections of higher-dimensional data sets onto a map are challenging to analyze. To reduce their complexity, a density-based clustering algorithm is employed to cluster map crossings by the geometry of their associated trajectories. By grouping the data into clusters and identifying representative trajectories in each cluster, a reduced data set is constructed. This smaller data set reduces the complexity of analysis. This data mining approach to leveraging Poincaré maps in the trajectory design process is explored in the circular restricted three-body problem.

[View Full Paper]

* Assistant Professor, Colorado Center for Astrodynamics Research, Smead Department of Aerospace Engineering Sciences, University of Colorado Boulder, 431 UCB, Boulder, Colorado 80309, USA.

LARGE SPACE STRUCTURES AND TETHERS

Session Chairs:

Session 13: Ryan Russell, The University of Texas at Austin

IDENTIFICATION OF STIFFNESS AND DAMPING MATRICES OF HIGH DEGREE-OF-FREEDOM STRUCTURAL MODELS

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

A method to identify the stiffness and damping matrices of high degree-of-freedom structural models is described. The number of degrees of freedom is considered high if the state-space model of the correct dimension from force inputs to measured outputs becomes uncontrollable and cannot be identified from input-output measurements, thus rendering standard state-space based physical parameter identification methods unusable. This difficulty is overcome by identifying the physical parameters associated with each individual degree of freedom where controllability is not compromised. These parameters are aggregated to form the global stiffness and damping matrices of the entire structure. [View Full Paper]

[*] Superior Information Technology, Inc., Banchiao, New Taipei City 22041, Taiwan.
[†] Thayer School of Engineering, Dartmouth College, Hanover, New Hampshire 03755, USA.
[‡] Mechanical Engineering, Columbia University, 500 West 120th Street, MC4703, New York, New York 10027, USA.

PARTIAL SYSTEM IDENTIFICATION OF STIFFNESS AND DAMPING MATRICES FROM OUTPUT MEASUREMENTS ONLY

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

This paper deals with the partial system identification of stiffness and damping matrices of a structure from output measurements only. The input forces that excite the structure are unknown and cannot be treated as white noise. This is a common scenario in practice where a structure is richly instrumented with accelerometers, yet the forces that excite the structure are unknown or unmeasured. This paper shows that if the mass matrix is known then the rows of the stiffness and damping matrices associated with the degrees of freedoms that are not directly actuated can still be recovered. [View Full Paper]

[*] Thayer School of Engineering, Dartmouth College, Hanover, New Hampshire 03755, USA.
[†] Superior Information Technology, Inc., Banchiao, New Taipei City 22041, Taiwan.
[‡] Mechanical Engineering, Columbia University, 500 West 120th Street, MC4703, New York, New York 10027, USA.

OPTIMAL CONTROL OF SPACE DEBRIS DEORBIT USING SPACE TETHERED SYSTEM

Pengjie Li,[*] Rui Zhong[†] and Hongwen Wang[‡]

This paper proposes an optimal control scheme for space debris deorbit by a space tethered system (TSS) with minimal fuel consumption. The scheme includes two phases, the open-loop control trajectory optimization and the closed-loop optimal control. The first phase, the open-loop control trajectory optimization, is derived by solving an optimal deorbit problem of the TSS using a direct collocation method based on Gauss pseudospectral method. The second phase concerns the closed-loop optimal control for tracking the optimal reference trajectory using the model predictive control method. Numerical results show that the proposed scheme can achieve space debris deorbiting to a graveyard orbit safely, economically and efficiently. [View Full Paper]

[*] Master Candidate, School of Astronautics, Beihang University, Beijing 100191, China.
[†] Associate Professor, School of Astronautics, Beihang University, Beijing 100191, China.
[‡] Master Candidate, School of Astronautics, Beihang University, Beijing 100191, China.

A MULTIDISCIPLINARY PERFORMANCE ANALYSIS FOR THE CYGNUS CARGO RESUPPLY MISSION TO THE ISS*

Virgil L. Hutchinson, Jr.†

The Cygnus propellant is a critical flight resource, and consumption analysis is performed for every CRS mission to determine the propellant load required to complete the mission with adequate propellant contingency and margin. An integrated analysis model involving several coupled analyses is used to generate the propellant budget by calculating the propellant usage for each maneuver during the CRS mission. Mission and configuration parameters within the integrated analysis model were varied probabilistically by performing a Monte Carlo analysis. Statistical distributions for the propellant usage from the Monte Carlo analysis are used to determine the recommended propellant load for the mission. [View Full Paper]

† Senior Manager, Systems Engineering, Innovation Systems, Northrop Grumman, 45101 Warp Drive, Dulles, Virginia 20166, USA.

AAS 19-363

HIGH-FIDELITY DYNAMIC MODELLING OF PARTIAL SPACE ELEVATOR WITH DEPLOYMENT OR RETRIEVAL OF TETHER

Zheng H. Zhu* and Gangqiang Li†

In this paper, a compressive model for the partial space elevator system undergoes deployment or retrieval is proposed. The model is built up based on the nodal position finite element method in the arbitrary Lagrangian-Eulerian framework. The movement of climber along the tether and the deployment or retrieval of tether at the end satellites are accomplished through the moving nodes and variable-length elements. The numerical results show that the effects of the high order transverse oscillation influence the dynamic behaviors of partial space elevator system must be considered. Furthermore, cases with different rates of deployment or retrieval are examined. It shows that the deployment of tether at the end satellites produce a positive effect to suppress the libration motion of PSE system, and the retrieval of tether produce a negative effect. [View Full Paper]

* Professor, Department of Mechanical Engineering, York University, 4700 Keele Street, Toronto, Ontario, Canada M3J 1P3. E-mail: gzhu@yorku.ca. (Corresponding author).

† PhD Candidate, Department of Earth and Science Space and Engineering, York University, 4700 Keele Street, Toronto, Ontario, Canada M3J 1P3.

AAS 19-365

FLIGHT DYNAMICS AND CONTROL STRATEGY OF FLEXIBLE ELECTRIC SOLAR WIND SAIL

Zheng H. Zhu,* Gangqiang Li† and Chonggang Du‡

A high-fidelity multiphysics model of an electric solar wind sail is developed by the nodal position finite element method. The coupling effects between the orbital and self-spinning motion are analyzed when the system subjects to the gravitational force only, and major coupling terms are identified and examined. The numerical simulations also show that the coupling effect between the orbital and self-spinning motions causes a periodic variation of the self-spin rate of E-sail and the tether tension. [View Full Paper]

* Professor, Department of Mechanical Engineering, York University, 4700 Keele Street, Toronto, Ontario, Canada M3J 1P3. E-mail: gzhu@yorku.ca. (Corresponding author).
† PhD Candidate, Department of Earth and Science Space and Engineering, York University, 4700 Keele Street, Toronto, Ontario, Canada M3J 1P3.
‡ PhD Candidate, Department of Earth and Science Space and Engineering, York University, 4700 Keele Street, Toronto, Ontario, Canada M3J 1P3.

AAS 19-369

PARALLEL OPTIMAL CONTROL FOR PARTIAL SPACE ELEVATOR

Zheng H. Zhu* and Gefei Shi†

A new piecewise parallel optimal control scheme to suppress the libration of a partial space elevator is developed. The libration is controlled by regulating tether length. The original optimal control scheme is split into two parallel phases on a dual-CPU system to reduce computational burden. CPU I predicts an optimal reference state trajectory for the next time interval piecewise by an open-loop optimization with a grossly simplified three-body tethered system model. CPU II tracks the predicted reference trajectory at the current time interval simultaneously by a closed-loop receding horizon control using a full dynamic model. The simulation results reveal that the newly proposed parallel optimal control scheme is able to suppress the libration of the partial space elevator by controlling tether tension only. [View Full Paper]

* Professor, Department of Mechanical Engineering, York University, 4700 Keele Street, Toronto, Ontario, Canada M3J 1P3. E-mail: gzhu@yorku.ca. (Corresponding author).

† Visiting PhD Student, Department of Mechanical Engineering, York University, 4700 Keele Street, Toronto, Ontario, Canada M3J 1P3.

AAS 19-370

NANOSATELLITE MISSION FOR SPACE DEBRIS DEORBIT DEMONSTRATION BY ELECTRODYNAMIC TETHER

Zheng H. Zhu*

Electrodynamic space tethers (EDT) have unique capabilities to provide cost-effective demonstrations of innovative concepts and acquire science data which would otherwise not be achievable on Earth. Over the past four decades, the development of space tether technology has witnessed 26 suborbital and orbital flights. These missions demonstrated that space tether technology has the near-term potential to meet a broad range of scientific and engineering demands. This paper will cover the mission concept study, mission objectives, nanosatellite design, hardware selection, and operation. [View Full Paper]

* Professor, Department of Mechanical Engineering, York University, 4700 Keele Street, Toronto, Ontario, Canada M3J 1P3. E-mail: gzhu@yorku.ca. (Corresponding author).

PROXIMITY MISSIONS AND FORMATION FLYING

Session Chairs:

Session 19: Brett Newman, Old Dominion University

Session 23: Roby Wilson, Jet Propulsion Laboratory

Session 27: Mauro Massari, Politecnico di Milano

The following paper was not available for publication:

AAS 19-314 Paper Withdrawn

EXACT KEPLERIAN RELATIVE MOTION: AN ELEMENTARY FORMULATION OF THE INITIAL-VALUE PROBLEM

Paul W. Schumacher, Jr.,[*] Wesley L. Jackson[†] and Ryan T. Olson[‡]

This paper presents the explicit solution for the initial-value problem of exact nonlinear relative motion between satellites in Keplerian orbits. The elementary approach taken here is designed to complement several more advanced mathematical formulations published by other authors in recent years, and can be used to represent the relative motion between any two orbits having non-zero angular momentum. For practical reasons, the analysis in this paper is limited to the case of elliptical chief and deputy orbits. Formulas are given for computing the relative motion of the deputy in terms of initial conditions, both in any inertially-oriented frame centered on the chief and in the usual Euler-Hill frame. Several numerical examples confirm the correctness and expected accuracy of the solution formulas. [View Full Paper]

[*] Principal Investigator in Astrodynamics for Space Situational Awareness, Air Force Research Laboratory RDSM, 550 Lipoa Parkway, Kihei, Hawaii 96753, USA.
[†] Cadet First Class, Department of Astronautics, U. S. Air Force Academy, Colorado Springs, Colorado 80920, USA.
[‡] Cadet First Class, Department of Astronautics, U. S. Air Force Academy, Colorado Springs, Colorado 80920, USA.

AAS 19-258

SPACECRAFT FORMATIONS USING ARTIFICIAL POTENTIAL FUNCTIONS AND RELATIVE ORBITAL ELEMENTS

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

The automated control of spacecraft formations in specified relative orbits is a challenging problem that is computationally intensive using traditional methods of numerically integrating trajectories and applying optimal control theory. In this paper, relative orbital elements and artificial potential functions are combined into a methodology that allows full control of the relative orbits of spacecraft formations. This method enables the intuitive design of geometrically complex formations, and allows collision avoidance during the formation establishment. The effectiveness of the control algorithm is illustrated with the numerical simulation of the establishment of a spacecraft swarm on two circular relative orbits. [View Full Paper]

[*] PhD Candidate, School of Aeronautics and Astronautics, Purdue University, West Lafayette, Indiana 47907, USA.
[†] Associate Professor, School of Aeronautics and Astronautics, Purdue University, West Lafayette, Indiana 47907, USA.

SIMULTANEOUS LOCALIZATION AND MAPPING FOR SATELLITE RENDEZVOUS AND PROXIMITY OPERATIONS USING RANDOM FINITE SETS

Lauren Schlenker,[*] Mark Moretto,[†] David Gaylor[‡] and Richard Linares[§]

Future space missions require that spacecraft have the capability to autonomously navigate non-cooperative environments for rendezvous and proximity operations (RPO). Current relative navigation filters can have difficulty in these situations, diverging due to complications with data association, high measurement uncertainty, and clutter, particularly when detailed a priori maps of the target object or spacecraft do not exist. The goal of this work is to demonstrate the feasibility of random finite set (RFS) filters for spacecraft relative navigation and pose estimation. The approach is to formulate satellite relative navigation and pose estimation as a simultaneous localization and mapping (SLAM) problem, in which an observer spacecraft seeks to simultaneously estimate the location of features on a target object or spacecraft as well as its relative position, velocity and attitude. This work utilizes a filter developed using the framework of RFS which are well suited to multi-target SLAM operations, avoiding data association entirely. Relevant RPO scenarios with simulated flash LIDAR measurements are tested with a Probability Hypothesis Density (PHD) RFS filter embedded in a particle filter to obtain a feature map of a target and a relative pose estimate between the target and observer. Preliminary results show that an RFS-based filter can successfully perform SLAM in a spacecraft relative navigation scenario with no a priori map of the target. These results demonstrate the feasibility of RFS filtering for spacecraft relative navigation and motivate future studies which may expand to tracking space objects for space situational awareness, as well as relative navigation around small bodies. [View Full Paper]

[*] Graduate Student, Aerospace Engineering and Mechanics, University of Minnesota, Minneapolis, Minnesota 55455, USA.
[†] Graduate Student, Aerospace Engineering Sciences, University of Colorado Boulder, Boulder, Colorado 80309, USA.
[‡] Aerospace Engineer, Navigation and Mission Design Branch, NASA Goddard Space Flight Center, Greenbelt, Maryland 20771, USA.
[§] Charles Stark Draper Assistant Professor, Department of Aeronautics and Astronautics, Massachusetts Institute of Technology, Cambridge, Massachusetts 02139, USA.

AAS 19-290

RELATIVE MOTION ANALYSIS USING THIRD- AND FOURTH-ORDER SOLUTIONS OF THE RELATIVE TWO-BODY PROBLEM

Julio César Benavides* and David B. Spencer†

In this paper, third-order and fourth-order, time-dependent solutions of the relative two-body problem are used in conjunction with the general equations of relative motion to analyze the relative motion of a chase vehicle with respect to a target vehicle at various orbital altitudes. The outcomes of this analysis are then compared to the outcomes that are derived from the Hill-Clohessy-Wiltshire equations. The results demonstrate that the third- and forth-order formulations provide a robust and comparable method of analyzing relative motion between two vehicles that is not hindered by the assumptions of linear orbit theory. [View Full Paper]

* Associate Professor, Department of Aerospace Engineering, Embry-Riddle Aeronautical University, 3700 Willow Creek Road, Prescott, Arizona 86301, USA. E-mail: julio.benavides1@erau.edu. AAS Member, AIAA Member.
† Professor, Department of Aerospace Engineering; Pennsylvania State University; 229 Hammond Building, University Park, Pennsylvania 16802, USA. E-mail: dbs9@psu.edu. Fellow, AAS; Associate Fellow, AIAA.

OUTPUT REGULATION CONTROL FOR SATELLITE FORMATION FLYING USING DIFFERENTIAL DRAG

Mohamed Shouman,[*] Mai Bando[†] and Shinji Hokamoto[‡]

This paper proposes a new hybrid control action of differentials aerodynamic drag and thrusters to control satellite formation flying in low Earth orbits. Parameterized output regulation algorithm for formation flying missions is developed based on the Schweighart-Sedwick relative dynamics equations. It is implemented to precisely track the different trajectories of reference relative motion and eliminates the effects of the J_2 perturbations. Parametric Lyapunov algebraic equation is derived to ensure the stability of the linear relative model subject to saturated inputs. The main goal of this study is to approve the viability of using the differentials in aerodynamic drag to precisely control different formation flying missions. Numerical simulations using a high fidelity relative dynamics model are implemented to analyze the performance of the proposed control algorithm in comparison with the linear quadratic regulator algorithm for actual satellite parameters. The paper exploits a high-precision orbit propagator model to verify the robustness of the control algorithm. [View Full Paper]

[*] Ph.D. Student, Department of Aeronautics and Astronautics, Kyushu University, Fukuoka 819-0395, Japan. E-mail: Mohamed.Shouman@aero.kyushu-u.ac.jp.

[†] Associate Professor, Department of Aeronautics and Astronautics, Kyushu University, Fukuoka 819-0395, Japan. E-mail: mbando@aero.kyushu-u.ac.jp. Member AIAA.

[‡] Professor, Department of Aeronautics and Astronautics, Kyushu University, Fukuoka 819-0395, Japan. E-mail: hokamoto@aero.kyushu-u.ac.jp. Member AIAA.

OPEN- AND CLOSED-LOOP NEURAL NETWORK CONTROL FOR PROXIMAL SPACECRAFT MANEUVERS*

Cole George,[†] Joshuah Hess[‡] and Richard Cobb[§]

Recent successes in machine learning research, buoyed by advances in computational power, have revitalized interest in neural networks and demonstrated their potential in solving complex controls problems. In this paper, such techniques are applied to the control of relative spacecraft motion. Open-loop and closed-loop feedback controllers, represented by multi-layer feed-forward artificial neural networks, are developed using evolutionary and gradient-based optimization. Constrained fixed-time, minimum control problems are solved using Clohessy-Wiltshire dynamics for intercept, rendezvous, and natural motion circumnavigation scenarios using three different thrust models: impulsive, finite, and continuous. In addition to optimality, robustness to parametric uncertainty and the generalized performance of these neurocontrollers are assessed. By bridging the gap between traditional optimal and nonlinear control techniques, this research shows that neural networks offer a flexible and robust alternative approach to the solution of complex controls problems in this domain and present a path forward to more capable, autonomous spacecraft. [View Full Paper]

* Approved for public release.

† M.S. Student, Department of Aeronautics and Astronautics, Air Force Institute of Technology, 2950 Hobson Way, Wright-Patterson AFB, Ohio 45433, USA.

‡ Assistant Professor, Department of Aeronautics and Astronautics, Air Force Institute of Technology.

§ Professor, Department of Aeronautics and Astronautics, Air Force Institute of Technology.

AAS 19-338

ANALYTICAL SPACECRAFT FORMATION DYNAMICS IN ECCENTRIC ORBITS WITH GRAVITATIONAL, DRAG AND THIRD-BODY PERTURBATIONS

Yazan Chihabi[*] and Steve Ulrich[†]

There has been a growing interest in spacecraft formation-flying for space science applications. Such missions will require an accurate and efficient dynamics model, on-board the flight computer, to calculate and control the desired relative motion. Hence, an analytical dynamics model which can be applied to eccentric orbits and includes perturbations can provide an increase in accuracy and efficiency. This paper achieves an accurate analytical solution of relative motion between two spacecrafts using each spacecraft's classical orbital elements. The analytical solution is obtained by propagating the orbital elements forward in time, while taking into account gravitational field up to the fifth harmonic, third-body and drag secular and periodic perturbations, and calculating the relative motion in the local-vertical-local-horizontal reference frame at each time-step. The analytical solution was observed to accurately describe the relative motion when compared with a numerical simulator, yielding errors on the order of meters for separation distances on the order of hundreds of meters. [View Full Paper]

[*] Research Assistant, Department of Mechanical and Aerospace Engineering, Carleton University, 1125 Colonel By Drive, Ottawa, ON, K1S 5B6, Canada.
[†] Associate Professor, Department of Mechanical and Aerospace Engineering, Carleton University, 1125 Colonel By Drive, Ottawa, ON, K1S 5B6, Canada.

RELATIVE MANEUVERING FOR MULTIPLE SPACECRAFT VIA DIFFERENTIAL DRAG USING LQR AND CONSTRAINED LEAST SQUARES

Camilo Riano-Rios,* Riccardo Bevilacqua† and Warren E. Dixon‡

In this paper, a set of spacecraft consisting of multiple chasers and a single target is considered for rendezvous and along-orbit formation maneuvers. Each spacecraft can change its experienced drag acceleration by extending/retracting drag surfaces. First, the relative states of the linearized relative dynamics of each chaser-target pair are driven to zero using a Linear Quadratic Regulator (LQR). Then, a Constrained Least Squares (CLS) Problem is formulated to find the best achievable set of individual inputs to control all chasers under mutual constraints and actuator saturations. Tests using a multiple spacecraft simulation framework that includes J_2 perturbation and the NRLMSISE-00 atmospheric density model, are conducted to validate the robustness of the proposed algorithm along with a method that uses the along-orbit formation as an intermediate stage to reduce the risk of potential collisions. [View Full Paper]

* Ph.D. Student, Mechanical and Aerospace Department, University of Florida, E-mail: crianorios@ufl.edu.
† Associate Professor, Mechanical and Aerospace Department, University of Florida. E-mail: bevilr@ufl.edu.
‡ Ebaugh Professor, Mechanical and Aerospace Department, University of Florida. E-mail: wdixon@ufl.edu.
939 Sweetwater Drive, MAE-A211, Gainesville, Florida 32611-6250, USA.

NETWORK ARCHITECTURE FOR UWB-BASED RELATIVE NAVIGATION OF MULTIPLE SPACECRAFT IN FORMATION FLIGHT

Nobuhiro Funabiki,* Satoshi Ikari,† Ryu Funase‡ and Shin-ichi Nakasuka§

Navigation and mutual communication are indispensable functions to manage a spacecraft formation flight. To achieve these functions, this paper presents a navigation and communication network architecture based on ultra-wide band (UWB) communication devices, which have been widely used for many applications like indoor-localization and navigation. By measuring distances between pairs of spacecraft, it is possible to estimate the relative positions and velocities of spacecraft in the formation. When it comes to a large-scale formation, a limited number of distances between two spacecraft can be measured by UWB devices at any one time due to physical limitations, such as available communications bandwidth. In this sense, it is necessary to select measured pairs of spacecraft to efficiently achieve high estimation accuracy. We propose an algorithm for the optimal selection of measure pairs of spacecraft to increase the estimation accuracy of the positions of spacecraft in the formation. The performance of the proposed method is evaluated in the simulation. [View Full Paper]

* Graduate Student, The University of Tokyo, 7-3-1 Hongo Bunkyo-ku Tokyo 113-8656 Japan. Tel: +81-3-5841-6631. E-mail: funabiki@space.t.u-tokyo.ac.jp.

† Assistant Professor, The University of Tokyo, 7-3-1 Hongo Bunkyo-ku Tokyo 113-8656 Japan, Tel: +81-3-5841-6631. E-mail: ikari@space.t.u-tokyo.ac.jp.

‡ Associate Professor, The University of Tokyo, 7-3-1 Hongo Bunkyo-ku Tokyo 113-8656 Japan, Tel: +81-3-5841-6631. E-mail: funase@space.t.u-tokyo.ac.jp.

§ Professor, The University of Tokyo, 7-3-1 Hongo Bunkyo-ku Tokyo 113-8656 Japan, Tel: +81-3-5841-6631, E-mail: nakasuka@space.t.u-tokyo.ac.jp.

AAS 19-350

POSE ESTIMATION FOR NON-COOPERATIVE SPACECRAFT RENDEZVOUS USING NEURAL NETWORKS

Sumant Sharma[*] and Simone D'Amico[†]

This work introduces the Spacecraft Pose Network (SPN) for on-board estimation of the pose, i.e., the relative position and attitude, of a known non-cooperative spacecraft using monocular vision. In contrast to other state-of-the-art pose estimation approaches for spaceborne applications, the SPN method does not require the formulation of hand-engineered features and only requires a single grayscale image to determine the pose of the spacecraft relative to the camera. The SPN method uses a Convolutional Neural Network (CNN) with three branches to solve the problems of relative attitude and relative position estimation. The first branch of the CNN bootstraps a state-of-the-art object detection algorithm to detect a 2D bounding box around the target spacecraft in the input image. The region inside the 2D bounding box is then used by the other two branches of the CNN to determine the relative attitude by initially classifying the input region into discrete coarse attitude labels before regressing to a finer estimate. The SPN method then uses a novel Gauss-Newton algorithm to estimate the relative position by using the constraints imposed by the detected 2D bounding box and the estimated relative attitude. The secondary contribution of this work is the generation of the Spacecraft PosE Estimation Dataset (SPEED), which is used to train and evaluate the performance of the SPN method. SPEED consists of synthetic as well as actual camera images of a mock-up of the Tango spacecraft from the PRISMA mission. The synthetic images are created by fusing OpenGL-based renderings of the spacecraft's 3D model with actual images of the Earth captured by the Himawari-8 meteorological satellite. The actual camera images are created using a 7 degrees-of-freedom robotic arm, which positions and orients a vision-based sensor with respect to a full-scale mock-up of the Tango spacecraft. Custom illumination devices simulate the Earth albedo and Sun light with high fidelity to emulate the illumination conditions present in space. The SPN method, trained only on synthetic images, produces degree-level relative attitude error and cm-level relative position errors when evaluated on the actual camera images not used during training. [View Full Paper]

[*] Ph.D. Candidate, Department of Aeronautics and Astronautics, Stanford University, 496 Lomita Mall, Stanford, California 94305, USA.

[†] Assistant Professor, Department of Aeronautics and Astronautics, Stanford University, 496 Lomita Mall, Stanford, California 94305, USA.

SECOND-ORDER ANALYTICAL SOLUTION FOR RELATIVE MOTION ON ARBITRARILY ECCENTRIC ORBITS

Matthew Willis,[*] Alan Lovell[†] and Simone D'Amico[‡]

A new, second-order solution for the relative position and velocity of two spacecraft on Keplerian orbits of arbitrary eccentricity is introduced. By normalizing the coordinates, changing the independent variable from time to true anomaly, and treating the higher-order terms as a perturbation of the resulting linear, time-varying system, the dynamics are rendered in a readily solvable form. A comparison of error trends against eccentricity and inter-spacecraft separation is presented between the new solution and several prominent translational state solutions from the literature. The new solution offers several orders of magnitude improvement in accuracy over existing first- and second-order solutions when evaluated against the underlying Keplerian motion model. [View Full Paper]

[*] PhD Candidate, Department of Mechanical Engineering, Stanford University, 496 Lomita Mall, Stanford, California 94305, USA.
[†] Space Vehicles Directorate, Air Force Research Laboratory, Kirtland AFB, New Mexico 87116, USA.
[‡] Professor, Department of Aeronautics and Astronautics, Stanford University, 496 Lomita Mall, Stanford, California 94305, USA.

AAS 19-367

AUTONOMOUS SPACECRAFT RENDEZVOUS BY LINE-OF-SIGHT CONTROL

Zheng H. Zhu* and Peng Li†

The paper investigates the autonomous spacecraft rendezvous by line-of-sight control. Nonlinear model predictive control method is applied for the problem and it is formulated in terms of line-of-sight range and azimuth angle. The numerical results show that the newly proposed line-of-sight nonlinear model predictive control scheme is able to effectively generate optimized approach trajectories with satisfactory control accuracy and the proposed method is insensitive to the measurement uncertainties. [View Full Paper]

* Professor, Department of Mechanical Engineering, York University, 4700 Keele Street, Toronto, Ontario, Canada M3J 1P3. E-mail: gzhu@yorku.ca. (Corresponding author).

† PhD Candidate, Department of Earth and Science Space and Engineering, York University, 4700 Keele Street, Toronto, Ontario, Canada M3J 1P3.

CONTROLLABILITY ANALYSIS OF PROPELLANT-FREE SATELLITE FORMATION FLIGHT

Mohamed Shouman,* Mai Bando† and Shinji Hokamoto‡

This paper proposes the controllability analysis of relative motion using different configurations for hybrid control actions of space environmental forces. It tends to present a minimal configuration for the missions exploiting these forces. It illustrates the constraints in each space environmental force and analyzes the integration between these forces to achieve full controllability of the satellite formation flight for near-circular low earth orbits with different orbit configurations. The paper implements a Kalman decomposition approach to decompose the system into controllable and uncontrollable subspaces for linear time-invariant control actions. Numerical simulations are investigated to study the controllability analysis for nonlinear models and substantiate the success of the controllability study for all hybrid control actions with different orbit configurations. [View Full Paper]

* Ph.D. Student, Department of Aeronautics and Astronautics, Kyushu University, Fukuoka 819-0395, Japan.
E-mail: Mohamed.Shouman@aero.kyushu-u.ac.jp. Member AIAA.
† Associate Professor, Department of Aeronautics and Astronautics, Kyushu University, Fukuoka 819-0395, Japan.
E-mail: mbando@aero.kyushu-u.ac.jp. Member AIAA.
‡ Professor, Department of Aeronautics and Astronautics, Kyushu University, Fukuoka 819-0395, Japan.
E-mail: hokamoto@aero.kyushu-u.ac.jp. Member AIAA.

PROXIMITY OPERATIONS WITH OBSTACLES AVOIDANCE BASED ON ARTIFICIAL POTENTIAL FIELD AND SLIDING MODE CONTROL

N. Bloise,[*] E. Capello[†] and E. Punta[‡]

This paper combines Guidance and Control (GC) algorithms for spacecraft proximity operations in presence of multiple obstacles. The proposed guidance algorithm is based on Artificial Potential Field (APF) theory, while the adopted control strategies are first-order Sliding Mode Control (SMC) algorithms. The position control problem is addressed by considering two different first-order methods: the simplex-based and the component-wise SMC. Both control strategies result to be effective and suitable to be implemented by the mono-directional actuation system. These algorithms are suitably designed for a ground test-bed for spacecraft rendezvous and docking experiments, developed within the STEPS project (Systems and Technologies for Space Exploration). The selected algorithms are suitable for autonomous, real-time control of proximity maneuvers with a minimum on-board computational effort. Moreover, the presented strategy is able to avoid obstacles and to manage issues related to the presence of local minima in APF algorithms. [View Full Paper]

[*] Graduate Researcher, Department of Mechanical and Aerospace Engineering, Politecnico di Torino, Corso Duca degli Abruzzi 24, 10129 Torino, Italy. E-mail: nicoletta.bloise@polito.it.
[†] Tenured Assistant Professor, Department of Mechanical and Aerospace Engineering and with the CNR–IEIIT, Politecnico di Torino, Corso Duca degli Abruzzi 24, 10129 Torino, Italy. E-mail: elisa.capello@polito.it.
[‡] Researcher, Institute of Electronics, Computer and Telecommunication Engineering, National Research Council of Italy (CNR-IEIIT), Torino, Italy. E-mail: elisabetta.punta@ieiit.cnr.it.

AAS 19-405

SPACECRAFT POSE ESTIMATION AND SWARM LOCALIZATION PERFORMANCE UNDER VARYING ILLUMINATION AND VIEWING CONDITIONS

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

Spacecraft swarm localization using relative pose measurements from passive cameras will be impacted by viewing conditions including relative solar angle and relative orientation between the target and the observer. This work attempts to assess the pose estimation performance across viewing geometries by simulating stereo images. The relative pose estimation error when using stereo vision and point cloud registration is computed. This error information is then incorporated into an Extended Kalman Filter cooperative localization scheme to determine the overall impact on swarm localization. An outlier rejection scheme is used to avoid spurious relative pose measurements and filter divergence.

[View Full Paper]

[*] Graduate Student, University of Southern California, Los Angeles, California, USA.
[†] David A. Barnhart, Research Professor, University of Southern California, Los Angeles, California, USA.

OPTIMAL INSPECTION OF A NADIR-POINTING SATELLITE WITH DYNAMIC ANGLE CONSTRAINTS

Mark R. Mercier* **and Kirk W. Johnson†**

Recent advancements in on-orbit proximity operations facilitate more complex inspection missions of active satellites with active sensors. These sensors can be simulated by keep-out zones; many will be nadir-pointing, but others may change direction in the local-horizontal/local-vertical frame. These keep-out zones define dynamic angle constraints for a satellite on a fuel-optimal inspection trajectory. This study will pose and solve the corresponding optimization problem using the multi-phase Gauss Pseudospectral Solver, GPOPS-II, with linearized Hill-Clohessy-Wiltshire dynamics. This solution method will allow for the flexibility to incorporate various dynamic keep-out zone constraints as well as desired viewing angle constraints. [View Full Paper]

* Graduate Student, Department of Aeronautics and Astronautics, Air Force Institute of Technology, WPAFB, Ohio 45433, USA.

† Assistant Professor, Department of Aeronautics and Astronautics, Air Force Institute of Technology, WPAFB, Ohio 45433, USA.

SAFE RENDEZVOUS TRAJECTORY DESIGN FOR THE RESTORE-L MISSION

Matthew A. Vavrina,[*] C. Eugene Skelton,[†] Keith D. DeWeese,[‡] Bo J. Naasz,[§] David E. Gaylor[**] and Christopher D'Souza[††]

The Restore-L mission will capture and robotically service Landsat 7 in the early 2020s. The rendezvous will be autonomous with onboard sensors providing relative navigation measurements and onboard guidance algorithms controlling to a reference trajectory. The trajectory design is predicated on maintaining passive safety through any fault until relative navigation is sufficiently accurate to proceed within proximity of Landsat 7. This requirement must be addressed with consideration for sensor range, measurement accuracy, dispersions, thruster faults, and lighting, among others. This paper presents the Restore-L rendezvous trajectory design, which incorporates a series of co-elliptic transfers for gradual far-field approach and periodic relative motion strategies for near-field approach and inspection. [View Full Paper]

[*] Senior Systems Engineer, a.i. solutions, Inc., Lanham, Maryland 20706, USA.
[†] Aerospace Engineer, NASA Goddard Space Flight Center (Code 480), SAIC, Greenbelt, Maryland 20771, USA.
[‡] Aerospace Engineer, NASA Goddard Space Flight Center (Code 591), Greenbelt, Maryland 20771, USA.
[§] NASA System Capability Lead for Rendezvous and Capture, NASA Headquarters, Washington, D.C. 20546, USA.
[**] Aerospace Engineer, NASA Goddard Space Flight Center (Code 595), Greenbelt, Maryland 20771, USA.
[††] GN&C Autonomous Flight Systems Engineer, NASA Johnson Space Center, Houston, Texas 77058, USA.

AAS 19-416

SATELLITE FORMATION FLYING: ON-GROUND EXPERIMENT ON RELATIVE ORBIT ELEMENTS-BASED CONTROL

E. Ausay,[*] L. Bassett-Audain,[†] L. DeWitte,[†] B. Paz,[†] A. Rajbhandary,[†] G. Di Mauro[‡] and R. Bevilacqua[§]

Accurate preflight testing environments for formation flying are crucial in transitioning between numerical simulation and actual orbital flight. A 3 degree of freedom (DOF) experimental testbed was developed at the Advanced Autonomous Multiple Spacecraft (ADAMUS) laboratory to validate a relative orbit elements-based control strategy for satellite formation reconfiguration maneuvering. The experimental facility consists of two completely autonomous vehicles floating on an epoxy 4×4 m surface. The vehicles are equipped with compressed air thrusters to enable their movement on the frictionless floor while a PhaseSpace Impulse System determines their position and attitude. A numerical simulator describing the dynamics of the testbed was developed, using MATLAB and Simulink, to have a benchmark for cross checking experimental results. This paper presents the design and integration of the vehicles with their preliminary experimental results. An experiment based on an analytical control scheme of 3 tangential (T-T-T) finite-time maneuvers was conducted to generate a guidance. A feedback control law using a Linear Quadratic Regulator (LQR) was implemented to follow the guidance. The vehicle was able to accurately track a computed guidance trajectory within the accuracy of 0.06 m. [View Full Paper]

[*] Graduate Student, Mechanical and Aerospace Engineering, University of Florida, 308 MAE-A Building, P.O. Box 116250 Gainesville, Florida 32611-6250, USA.
[†] Undergraduate Student, Mechanical and Aerospace Engineering, University of Florida, 308 MAE-A Building, P.O. Box 116250 Gainesville, Florida 32611-6250, USA.
[‡] Post-Doctoral Associate, Mechanical and Aerospace Engineering, University of Florida, 308 MAE-A Building, P.O. Box 116250 Gainesville, Florida 32611-6250, USA.
[§] Associate Professor, Mechanical and Aerospace Engineering, University of Florida, 308 MAE-A Building, P.O. Box 116250 Gainesville, Florida 32611-6250, USA.

AAS 19-430

LOW-THRUST RECONFIGURATION FOR FORMATION FLYING USING JORDAN NORMAL FORM THEORY

Xue Bai,[*] Ming Xu[†] and Yuying Liang[‡]

This Paper proposes a control strategy and optimization of low-thrust reconfiguration for formation flying by Jordan norm form to overcome the drawback of eigenvalue decomposition in describing the unstable term of the relative motion. In this Paper, the initial values of general solution from simplified dynamics are regarded as the invariants of formation configuration. The derivation on control acceleration builds a functional from the initial configuration to the final one, which can be approximated by polynomial series. Thus, the selection of time sequence of low thrust can be converted into a parametrical optimization problem that can be achieved by elementary optimization functions. The numerical results show that this proposed strategy realizes the formation reconfiguration with low control acceleration in an orbit period successfully. [View Full Paper]

[*] Undergraduate, School of Astronautics, Beihang University, Beijing 100191, China.
[†] Associate Professor, School of Astronautics, Beihang University, Beijing 100191, China.
[‡] Post-Doctoral Fellowship, Department of Mechanical Engineering, York University, 4700 Keele Street, Toronto, Ontario, Canada M3J 1P3.

IMPACT OF INTERNAL HEATING ON SPACECRAFT THERMAL SIGNATURE

Scott Carnahan,[*] Hanspeter Schaub[†] and Benjamin Lane[‡]

Vision-based relative navigation of spacecraft in the thermal infrared is a burgeoning area of research. The asymmetry of spacecraft thermal systems could be used to identify the attitude of a symmetric object using the infrared spectrum that would be challenging in the visible spectrum. Spacecraft internal thermal signatures have not been focused on in thermal relative navigation research. In order to investigate this, two simulation tools are built for the Basilisk astrodynamics framework developed by the Autonomous Vehicle System lab at CU Boulder. The first is a thermal modeling package. The second is a thermal camera module which allows for closed-loop image generation of spacecraft with thermal system models. The closed-loop capability of the camera is unique among spacecraft thermal image simulation tools. The camera and thermal package are demonstrated together in a closed-loop two-spacecraft dynamics scenario. [View Full Paper]

[*] Draper Graduate Fellow, Department of Aerospace Engineering Sciences, University of Colorado, 431 UCB, Colorado Center for Astrodynamics Research, Boulder, Colorado 80309-0431, USA.

[†] Professor and Glenn L. Murphy Endowed Chair of Engineering, Department of Aerospace Engineering Sciences, University of Colorado, 431 UCB, Colorado Center for Astrodynamics Research, Boulder, Colorado 80309-0431, USA. AAS Fellow.

[‡] Group Leader, Advanced Position, Navigation & Timing Instrumentation, 555 Technology Square, Cambridge, Massachusetts 02139, USA.

AAS 19-475

3-DIMENSIONAL REACHABLE SET APPLICATIONS TO MULTI-SPACECRAFT TRAJECTORY COORDINATION

Chandrakanth Venigalla[*] and Daniel J. Scheeres[†]

To work towards advancing mission design capabilities for spacecraft formations and constellations, we investigate the application of reachable sets to solve trajectory coordination problems. We generate three-dimensional reachable sets that give the set of reachable orbits for a given spacecraft in semimajor axis-eccentricity-inclination space. We then use the sets to explore optimal rendezvous orbits for systems of 2 and more spacecraft. Rendezvous optimality criteria includes, but is not limited to total ΔV. We further investigate how these sets allow us to find optimal evasion strategies. [View Full Paper]

[*] Ph.D. Student, Department of Aerospace Engineering Sciences, University of Colorado Boulder, Colorado 80309, USA.

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

RANDOM FINITE SET THEORY AND OPTIMAL CONTROL OF LARGE SPACECRAFT SWARMS

Bryce Doerr,[*] Richard Linares,[†] Pingping Zhu[‡] and Silvia Ferrari[§]

Controlling large swarms of robotic agents has many challenges including, but not limited to, computational complexity due to the number of agents, uncertainty in the functionality of each agent in the swarm, and uncertainty in the swarm's configuration. This work generalizes the swarm state using Random Finite Set (RFS) theory and solves the control problem using Model Predictive Control (MPC) to overcome the aforementioned challenges. Computationally efficient solutions are obtained via the Iterative Linear Quadratic Regulator (ILQR). Information divergence is used to define the distance between the swarm RFS and the desired swarm configuration. Then, a stochastic optimal control problem is formulated using a modified L_2^2 distance. Simulation results using MPC and ILQR show that swarm intensities converge to a target destination, and the RFS control formulation can vary in the number of target destinations. ILQR also provides a more computationally efficient solution to the RFS swarm problem when compared to the MPC solution. Lastly, the RFS control solution is applied to a spacecraft relative motion problem showing the viability for this real-world scenario. [View Full Paper]

[*] Ph.D. Student, Department of Aerospace Engineering and Mechanics, University of Minnesota, Minneapolis, Minnesota 55455, USA.
[†] Charles Stark Draper Assistant Professor, Department of Aeronautics and Astronautics, Massachusetts Institute of Technology, Cambridge, Massachusetts 02139, USA.
[‡] Research Associate, Department of Mechanical and Aerospace Engineering, Cornell University, Ithaca, New York 14853, USA.
[§] Professor, Department of Mechanical and Aerospace Engineering, Cornell University, Ithaca, New York 14853, USA.

RAPID ALGORITHM TO DETERMINE THE CLOSE APPROACHES AND DURATIONS BETWEEN SATELLITES

Huijiang Wang,[*] Xiucong Sun,[†] Chao Han[‡] and Hongwen Wang[§]

A rapid algorithm to determine the satellite close approaches is presented in this paper. This paper first proposes ellipsoidal and spherical models of avoidance region to describe the close approaches and encounter functions are formulated to determine the entry and exit opportunities between two satellites. An adaptive piecewise interpolation technique featured with autonomously searching for the interpolation points is then presented to rapidly and accurately approximate the waveform of encounter function. Numerical simulations indicate that compared with the exhaustive search method the adaptive algorithm achieves over 99% decrease in computation time while guarantees adequate accuracy. [View Full Paper]

[*] Postgraduate Student, School of Astronautics, Beihang University, Beijing 100191, China.
[†] Lecturer, School of Astronautics, Beihang University, Beijing 100191, China. (Corresponding author).
[‡] Professor, School of Astronautics, Beihang University, Beijing 100191, China.
[§] Postgraduate Student, School of Astronautics, Beihang University, Beijing 100191, China.

FRACTIONAL CONTROL IN LINEARIZED RELATIVE-ORBIT DYNAMICS

David Yaylali,[*] Eric Butcher[†] and Andrew J. Sinclair[‡]

Fractional control strategies for linearized relative-orbit dynamics are introduced and compared to standard proportional-derivative control strategies. Using fractional derivative operators in the controller introduces additional tunable degrees of freedom, affording more freedom in shaping the controlled trajectory. As a result, more optimal rendezvous trajectories can be achieved. Specifically, it is shown that fractional relative-orbit controllers outperform standard controllers in terms of several important performance measures such as settling time, overshoot, and control effort. [View Full Paper]

[*] MS Student, Department of Aerospace and Mechanical Engineering, University of Arizona, Tucson, Arizona 85721, USA.
[†] Professor, Department of Aerospace and Mechanical Engineering, University of Arizona, Tucson, Arizona 85721, USA.
[‡] Senior Aerospace Engineer, Space Vehicles Directorate, Air Force Research Laboratory, Kirtland AFB, New Mexico 87117, USA.

AAS 19-511

A TIP-TILT HARDWARE-IN-THE-LOOP AIR-BEARING TEST BED WITH PHYSICAL EMULATION OF THE RELATIVE ORBITAL DYNAMICS

Ayansola D. Ogundele,[*] Bautista R. Fernandez,[†] Josep Virgili-Llop[‡] and Marcello Romano[§]

A new hardware-in-the-loop (HIL) air bearing testbed that is capable of physically emulating the relative orbital dynamics is presented. Typically, air bearing testbeds consist of test vehicles operating on top of a planar and horizontally-leveled surface. These test vehicles use air bearings to reduce the friction with the operating surface to negligible levels. The low friction, combined with the horizontally-leveled surface, creates a low residual acceleration environment. These dynamics are representative of the environment that spacecraft experience during close proximity maneuvers. To extend the applicability of planar air bearing test beds to longer maneuvers or separations relative orbital dynamics need to be emulated. In this paper, using Hill-Clohessy-Wilshire dynamics, we emulated the relative orbital dynamics of a real spacecraft using a scaled Floating Spacecraft Simulator (FSS) on a dynamically inclined operating surface. The mathematical constructs of the tilt angles, screw height displacements and scaling parameters are developed via Euler's rotation theorem, Buckingham's Pi theorem and the similarity principle. The applicability of the new idea is demonstrated via a circumnavigation maneuver scenario of a spacecraft in a Low Earth Orbit (LEO). The simulation results show the viability and suitability of the new approach. [View Full Paper]

[*] NRC Research Associate, Spacecraft Robotics Laboratory, Department of Mechanical and Aerospace Engineering, Naval Postgraduate School, 1 University Circle, Monterey, California 93943, USA.
[†] Faculty Associate, Adaptive Optics Center of Excellence, Spacecraft Research and Design Center, Department of Mechanical and Aerospace Engineering, Naval Postgraduate School, 1 University Circle, Monterey, California 93943, USA.
[‡] NRC Research Associate, Spacecraft Robotics Laboratory, Department of Mechanical and Aerospace Engineering, Naval Postgraduate School, 1 University Circle, Monterey, California 93943, USA.
[§] Professor, Spacecraft Robotics Laboratory, Department of Mechanical and Aerospace Engineering, Naval Postgraduate School, 1 University Circle, Monterey, California 93943, USA.

OPTIMAL RANGE OBSERVABILITY MANEUVERS FOR ANGLES-ONLY NAVIGATION IN ELLIPTIC ORBITS

Francisco J. Franquiz,[*] Bogdan Udrea[†] and Troy Henderson[‡]

A generalization of existing methods for planning optimal observability trajectories for spacecraft using angles-only measurements of a non-cooperative resident space object is proposed. The linearized dynamics are propagated using a state transition matrix[1] applicable to elliptical planetary orbits of arbitrary eccentricity. Together with a pseudo-time parameterization of relative trajectories, transfers between any two feasible flight paths can be calculated without the need for numerical integration.

The new approach uses a previously validated metric and objective function[2] to evaluate the observability along trajectories resulting from two different targeting methods. The first method imposes a fixed relation between the parameterizing pseudo-time variables to produce a single degree-of-freedom (DoF) optimization problem. The second method relaxes the relation between the variables to produce a more flexible, two DoF, problem, at the cost of terminal velocity constraints. In both cases the transfer between trajectories is constrained in terms of duration, fuel used per burn, the times at which the burns occur, and collision avoidance.

Numerical simulation results are used to compare representative examples of proximity operations in low Earth orbit at different eccentricities. A preliminary verification procedure is also presented which uses an unscented Kalman filter to produce navigation results and assess the performance of the trajectory planning methods. [View Full Paper]

[*] Ph.D. Candidate, Department of Aerospace Engineering, Embry-Riddle Aeronautical University, Daytona Beach, Florida 32114, USA. E-mail: franquif@my.erau.edu.

[†] Associate Professor, Department of Aerospace Engineering. E-mail: udreab@erau.edu.

[‡] Assistant Professor, Department of Aerospace Engineering. E-mail: hendert5@erau.edu.

AAS 19-539

ANALYSIS AND SIMULATION OF ROBOTIC HOPPING MANEUVERS INSIDE THE INTERNATIONAL SPACE STATION WITH ASTROBEE

Katrina P. Alsup,[*] Josep Virgili-Llop,[†] Justin Komma[‡] and Marcello Romano[§]

Hopping is an alternative mobility approach for intra and extravehicular robotics. In a hopping maneuver a spacecraft uses its robotic manipulator to execute a hop between two locations of the surface of the host spacecraft. A hopping maneuver is composed of three distinct phases: a manipulator-assisted push, a free-flying coast, and a manipulator-assisted propulsive free-flying coast, and a manipulator-assisted soft-landing. This class of maneuvers have the potential to use less propellant than the classical propulsive free-flying approach and, when compared to zero-g climbing, hopping can be more versatile and achieve shorter transit times. A detailed formulation of a three-dimensional hopping maneuver for intravehicular robotics is presented here. Using this formulation, a hopping maneuver for the Astrobee free-flyer is designed. The simulated maneuver shows Astrobee hopping between two handrails inside the International Space Station.

[View Full Paper]

[*] Graduate Student, Mechanical and Aerospace Engineering Department, 1 University Circle, Monterey, California 93940, USA. AIAA Member.

[†] NRC Postdoctoral Fellow, Mechanical and Aerospace Engineering Department, 1 University Circle, Monterey, California 93940, USA. AIAA Member.

[‡] Graduate Student, Mechanical and Aerospace Engineering Department, 1 University Circle, Monterey, California 93940, USA.

[§] Professor, Mechanical and Aerospace Engineering Department, 1 University Circle, Monterey, California 93940, USA. AIAA Associate Fellow; AAS Member.

AAS 19-582

ANALYSIS OF A SWARM DEPLOYMENT FOR VERY LOW EARTH ORBIT OPERATIONS

Bogdan Udrea*

A swarm of 12 space vehicles performs an Earth observation mission from a very low Earth circular orbit, at 200 km altitude. Deployment of the swarm from the upper stage of the launch vehicle has been identified as a critical phase of the mission. A deployment strategy has been found that sets up the swarm for success and results of the simulation performed with the Orbital Extrapolation Kit (Orekit) are presented to support this conclusion. [View Full Paper]

* Research Engineer, VisSidus Technologies, Inc, 601 Innovation Way, Daytona Beach, Florida 32114, USA.

SPACE SITUATIONAL AWARENESS AND FLIGHT DYNAMICS OPERATIONS

Session Chairs:

Session 21: Ryan Park, Jet Propulsion Laboratory and
Nathan Strange, Jet Propulsion Laboratory / California Institute of Technology

NEW HORIZONS 2014MU$_{69}$ (ULTIMA THULE) FLYBY DESIGN AND EXECUTION

Gabe D. Rogers,[*] Christopher B. Hersman,[†]
Alice F. Bowman[‡] and Ann P. Harch[§]

Since the encounter with the Pluto system in 2015, the New Horizons team had been preparing for a flyby of the Kuiper Belt Object 2014MU$_{69}$ (Ultima Thule). This paper discusses how the team designed and executed the flyby encounter within the various constraints imposed after the Pluto flyby. In addition to a brief overview of key spacecraft subsystems, this paper describes how the design needed to accommodate for large uncertainties in the target's position while minimizing image smear during science observations. The resource management, maneuver planning, and power and data downlink constraint management details are also explained. [View Full Paper]

[*] Principal Professional Staff, Space Exploration Sector, The Johns Hopkins University Applied Physics Laboratory, 11100 Johns Hopkins Road, Laurel, Maryland 20723, USA. E-mail: Gabe.Rogers@jhuapl.edu.

[†] Principal Professional Staff, Space Exploration Sector, The Johns Hopkins University Applied Physics Laboratory, 11100 Johns Hopkins Road, Laurel, Maryland 20723, USA. E-mail: Chris.Hersman@jhuapl.edu.

[‡] Principal Professional Staff, Space Exploration Sector, The Johns Hopkins University Applied Physics Laboratory, 11100 Johns Hopkins Road, Laurel, Maryland 20723, USA. E-mail: Alice.Bowman@jhuapl.edu.

[§] New Horizons Science Operations Uplink Technical Lead, Southwest Research Institute, 1050 Walnut Street. Suite 300, Boulder, Colorado 80302, USA. E-mail: harch@boulder.swri.edu.

AAS 19-383

ORBIT DETERMINATION SIMULATION FOR KOREA PATHFINDER LUNAR ORBITER USING SEQUENTIAL ESTIMATION APPROACH

Young-Rok Kim,* Young-Joo Song,† Jonghee Bae‡ and Seok-Weon Choi§

The Korea Pathfinder Lunar Orbiter (KPLO) is Korea's first lunar exploration program developed by the Korea Aerospace Research Institute and will be launched in late 2020. The KPLO will employ a 3.5 phasing loop and 100 km altitude lunar polar orbit for lunar transfer and mission phases, respectively. In this study, we introduced orbit determination (OD) strategy of KPLO flight dynamics system and demonstrated OD simulation results using sequential estimation technique. The lunar transfer trajectory and mission orbit of KPLO were simulated by STK and KPLO tracking measurements were generated by ODTK using simulated trajectory and ground station configuration including two Deep Space Networks and Korea Deep Space Antenna. For the trans-lunar phase, the orbit prediction (OP) results at the time of perigee maneuvers were presented for stable maneuver execution. For the lunar mission phase, OD and OP results were investigated for payload data processing and mission operation and planning. For OD accuracy assessments, the position uncertainty and orbit overlap precision were utilized. The uncertainties of Keplerian elements and the differences between estimated and true orbits were analyzed for evaluation of OP performance in trans-lunar and mission phases, respectively. Finally, we confirmed that the simulated OD and OP performance addresses the orbit requirements of KPLO. This study provides a useful guideline for the operation of KPLO for trans-lunar and lunar mission phases. [View Full Paper]

* Senior Researcher, Lunar Exploration Program Office, Korea Aerospace Research Institute, 169-84 Gwahak-ro, Yuseong-gu, Daejeon, 34133, Korea.

† Senior Researcher, Lunar Exploration Program Office, Korea Aerospace Research Institute, 169-84 Gwahak-ro, Yuseong-gu, Daejeon, 34133, Korea.

‡ Senior Researcher, Lunar Exploration Program Office, Korea Aerospace Research Institute, 169-84 Gwahak-ro, Yuseong-gu, Daejeon, 34133, Korea.

§ KPLO Program Manager, Lunar Exploration Program Office, Korea Aerospace Research Institute, 169-84 Gwahak-ro, Yuseong-gu, Daejeon, 34133, Korea.

AAS 19-474

SINGLE-WAYPOINT GUIDANCE FOR ROTATING TARGET FORMATION FLYING

Armando Rolins[*] and Brian D. Kaplinger[†]

This paper addresses an autonomous rendezvous procedure between two spacecraft in close proximity in which the chaser object is attempting to dock at a location on a rotating target. Previous approaches in the literature focus on offline optimization algorithms to generate an open-loop trajectory. This research proposes to use a fully closed-loop control to perform this kind of rendezvous and compares the cost attained by three different control laws given the same problem parameters. The proposed solution makes use of a single waypoint to avoid a trajectory which causes a collision while meeting all boundary conditions. It was found that the three control laws proposed are comparable in their cost under the same problem parameters and waypoint selection, but it was observed that the waypoint selection relates to the cost in a nonlinear fashion. The choice of waypoint based on position, velocity and time of flight to the waypoint was discussed and a search for a global minimum was conducted for each of the three control laws to identify the cost driving parameters. It was found that the problem of choosing the waypoint behaves similarly between the three control laws, and a few parameters governing waypoint efficacy are suggested. [View Full Paper]

[*] Quality Engineer, Embraer Executive Jets, 1111 General Aviation Drive, Melbourne, Florida 32935, USA.
[†] Deputy Director, Aldrin Space Institute, Florida Institute of Technology, 150 W. University Blvd., Melbourne, Florida 32901, USA.

AUTOMATED NEAR REAL-TIME VALIDATION AND DATA INTEGRITY ASSESSMENT USING AN UNSCENTED SCHMIDT KALMAN FILTER (USKF)

Tom Kelecy,[*] Emily Lambert,[†] Ben Sunderland[‡] and Jason Stauch[§]

There is a growing need to supplement the existing space surveillance sensor networks with additional sensors to support tracking and management of the ever-increasing population of both active and inactive Earth orbiting objects in and near the geosynchronous Earth orbit (GEO) belt. A globally distributed sensor network ensures timely and persistent monitoring of the space environment to help ensure safe use of space for communications, commerce, defense and Earth science missions. There is a need for rapid validation and near real-time data integrity monitoring to facilitate rapid incorporation of new or upgraded sensors into a network. The purpose of the work presented here is to develop an automated near real-time validation and data integrity process for rapid integration and evaluation of sensor data used to support tracking of Resident Space Objects (RSOs). A baseline set of optical sensor data, which included known reference objects, was simulated and analyzed to establish a test data set for the automated real-time sensor calibration and quality assessment. A dynamic filter implementation, using an Unscented Schmidt Kalman Filter (USKF), was developed which incorporates a near real-time estimation of noise and bias characteristics and includes facilitation of a near real-time reference satellite orbit state. Sensitivity to unmodeled error sources via Consider filtering was also examined for cases where a reference source is not available to support sensor calibration. The fusion of multiple data types and sources will also enable the distinction between filter "artifacts" due to data quality and anomalies versus un-modeled dynamics of the tracked objects in the estimation filter. [View Full Paper]

[*] Senior Research Scientist, L3-ADS, 10807 New Allegiance Drive, Colorado Springs, Colorado 80921, USA.
[†] Aerospace Engineer, L3-ADS, 10807 New Allegiance Drive, Colorado Springs, Colorado 80921, USA.
[‡] Aerospace Engineer, L3-ADS, 10807 New Allegiance Drive, Colorado Springs, Colorado 80921, USA.
[§] Aerospace Research Engineer, L3-ADS, 10807 New Allegiance Drive, Colorado Springs, Colorado 80921, USA.

AAS 19-534

REAL-TIME TELESCOPE TASKING FOR CUSTODY AND ANOMALY RESOLUTION USING JUDICIAL EVIDENTIAL REASONING

Daniel Aguilar Marsillach,[*] Shahzad Virani,[†] Marcus J. Holzinger,[‡] Moses W. Chan[§] and Prakash P. Shenoy[**]

As the near-Earth space object population increases in size, SSA sensor tasking becomes more complex. Most forms of tasking focus on covariance minimization, information maximization or catalog maintenance. Limited work has been done on tactical hypothesis-based sensor tasking, which resolves the problem from a decision-making perspective. Hypotheses can be formulated resolved using Dempster-Shafer evidential reasoning. Previous work lead to the formulation of Judicial Evidential Reasoning, resulting in optimal and unbiased hypothesis resolution under time constraints. This paper focuses on applying the Judicial Evidential Reasoning algorithm to resolve the anomaly and custody hypotheses of space objects using a telescope. The contributions in this paper include formulating new evidence to hypothesis belief mappings in Dempster-Shafer theory, incorporating a reachability set search action, and implementing the algorithm in real-time for a narrow field-of-view telescope. [View Full Paper]

[*] PhD Student, Ann & H.J. Smead Aerospace Engineering Sciences, University of Colorado Boulder, 2598 Colorado Ave, Boulder, Colorado 80309, USA.
[†] PhD Student, Ann & H.J. Smead Aerospace Engineering Sciences, University of Colorado Boulder, 2598 Colorado Ave, Boulder, Colorado 80309, USA.
[‡] Associate Professor, Ann & H.J. Smead Aerospace Engineering Sciences, University of Colorado Boulder, 2598 Colorado Ave, Boulder, Colorado 80309, USA.
[§] Technical Fellow, Lockheed Martin Space Systems, Sunnyvale, California 94089, USA.
[**] Distinguished Professor, School of Business, University of Kansas, 1654 Naismith Drive, Lawrence, Kansas 66045, USA.

LABEL ASSIGNMENTS IN CUBESAT CLUSTER DEPLOYMENT TRACKING

John A. Gaebler[*] and Penina Axelrad[†]

A Labeled Multi-Bernoulli (LMB) filter is used to estimate the states and *identities* of multiple CubeSats deployed in a cluster during the first few days in orbit. This work focuses on the label assignments in a scenario combining labeled measurements provided by operators with typical radar observations. When objects are clustered, there can be enough uncertainty (in positions and measurements) that labeled measurements cannot be perfectly associated with specific objects. A method is presented to probabilistically manage label assignments within the LMB framework. A simulation of the Planet Labs deployment of 88 CubeSats from PSLV-C37 launch demonstrates the approach.

[View Full Paper]

[*] PhD Candidate, Smead Aerospace Engineering Sciences, University of Colorado Boulder, Colorado 80309, USA. AIAA Member.

[†] Professor, Smead Aerospace Engineering Sciences, University of Colorado Boulder, Colorado 80309, USA. AIAA Fellow.

AAS 19-551

DISTANT RETROGRADE ORBIT CONSTELLATIONS FOR RELATIVE-ONLY NAVIGATION IN NEAR RECTILINEAR HALO ORBITS

Michael J. Volle*

NASA is currently working on the spacecraft and trajectory design for the Gateway mission that will reside in a Near Rectilinear Halo Orbit (NRHO). In the NRHO, Gateway will nominally require orbital maintenance maneuvers once per revolution. Separately, NASA is also working to develop technologies and techniques for relative navigation in cis-lunar space. Together, these concepts represent an opportunity for interesting research in cis-lunar navigation performance. Furthermore, Gateway is expected to be utilized for human spaceflight, and human activity will contribute to orbital disturbances of the vehicle, which typically degrades navigation performance. This work extends a previous work to examine various constellations of spacecraft in Distant Retrograde Orbits (DRO) for the purposes of relative navigation for Gateway under both crewed and unscrewed conditions. Results suggest multiple DRO spacecraft can provide improvements in navigation performance as compared to Deep Space Network (DSN) or single-DRO solutions. [View Full Paper]

* Principal Systems Engineer, a.i. solutions, Inc., 4500 Forbes Blvd., Suite 300, Lanham, Maryland 20706, USA. E-mail: michael.volle@ai-solutions.com.

AAS 19-563

COGITATION OF SPACE CURVE PRINCIPLES FOR LAPLACE ORBIT DETERMINATION

Brett Newman* and T. Alan Lovell†

This paper investigates the application of kinematic-geometric space curve principles to Laplace orbit determination methodology with the objective of exposing new insights, extracting new unknowns, and effectuating new computational solutions. The curve traced out on a unit sphere centered on the observer, by the satellite line-of-sight unit vector, is first established. The curve will necessarily pass through the line-of-sight measurement vectors, and differences between the behavior of points on-the-curve and corresponding interpolated points off-the-curve are discussed. The unit sphere curve is then described with a Frenet coordinate system consisting of tangential, normal, and bi-normal directions. The angular velocities of the Frenet axes and their relationship to the line-of-sight rates of change are developed and introduced. The angular velocity components provide new physical insights to the determination problem and facilitate fundamental parameter transparency. These components and their directions can be treated as unknowns or can be treated as parameters requiring recalibration using several strategies including physical or mathematical notions. Advantages of transforming measurement equations to the Frenet axes and/or transforming to angular velocity unknowns are explored and discussed. Several numeric examples are given to demonstrate the concepts and potential accuracy improvement. [View Full Paper]

* Professor, Department of Mechanical & Aerospace Engineering, Old Dominion University, ECSB 1317, Norfolk, Virginia 23529, USA.

† Research Aerospace Engineer, Air Force Research Laboratory, 3550 Aberdeen Ave. SE, Kirtland AFB, New Mexico 87117, USA.

ACCURATE AND ROBUST ESTIMATION METHOD OF AUTONOMOUS ORBIT DETERMINATION USING ACTIVE MANEUVERS AND INTER-SATELLITE RANGING

Kota Kakihara,[*] Naoya Ozaki,[†] Ryu Funase[‡] and Shinichi Nakasuka[§]

Autonomous orbit determination method using active maneuvers and inter-satellite ranging between multiple spacecraft is applicable to general dynamics situations, but large uncertainty of information about maneuvers results in inaccurate orbit estimation. This paper proposes an accurate and robust estimation method using sequential filter, RTS smoother, and EM algorithm. Proposed method estimates not only states but also maneuver results. Results from simulations of Mars-Phobos system show that the proposed method improve orbits determination accuracy. [View Full Paper]

[*] Graduate Student, Department of Aeronautics and Astronautics, The University of Tokyo, 7-3-1 Hongo, Bunkyo-ku, Tokyo 113-8656, Japan.
[†] Postdoctoral Researcher, Department of Space Flight Systems, ISAS/JAXA, 3-1-1 Yoshinodai, Chuo-ku, Sagamihara, Kanagawa 252-5210, Japan.
[‡] Associate Professor, Department of Aeronautics and Astronautics, The University of Tokyo, 7-3-1 Hongo, Bunkyo-ku, Tokyo 113-8656, Japan.
[§] Professor, Department of Aeronautics and Astronautics, The University of Tokyo, 7-3-1 Hongo, Bunkyo-ku, Tokyo 113-8656, Japan.

GUIDANCE, NAVIGATION, AND CONTROL

Session Chairs:

Session 22: Robyn Woollands, Jet Propulsion Laboratory
Session 25: Troy Henderson, Embry-Riddle Aeronautical University and Christopher Scott, The Johns Hopkins University Applied Physics Laboratory

The following paper was not available for publication:

AAS 19-435 Paper Withdrawn

UNSCENTED GUIDANCE FOR ZERO-FEEDBACK REACTION WHEEL SLEWS

Lara C. Magallanes* and Mark Karpenko†

Attitude control system failures are often mission ending even when the mission payload remains operational. In this paper, the concept of unscented guidance is applied to accurately reorient a reaction wheel satellite in the absence of feedback. It is shown that it is possible for a properly designed open-loop maneuver to achieve terminal attitude errors that are comparable with closed-loop control in the presence of uncertainty in the satellite inertia tensor. Following the open-loop maneuver, control can be handed over to a fine pointing control mode that uses other sensors, such as a fine guidance sensor or a star tracker to close the loop for science acquisition. The approach presented here enables large angle attitude control to be recovered so that operations may be continued, even in the event of a total rate gyroscope failure. [View Full Paper]

* PhD Student, Space Systems Academic Group, Naval Postgraduate School, Monterey, California 93943, USA.

† Research Associate Professor, Department of Mechanical Engineering, Naval Postgraduate School, Monterey, California 93943, USA. Corresponding author, E-mail: mkarpenk@nps.edu.

AAS 19-221

MODERN AEROCAPTURE GUIDANCE TO ENABLE REDUCED-LIFT VEHICLES AT NEPTUNE

C. R. Heidrich,* S. Dutta† and R. D. Braun‡

Aerocapture is covered extensively in the literature as means of achieving orbital insertion with dramatic mass-saving results compared to fully-propulsive systems. One of the primary obstacles facing aerocapture is the inherent uncertainty associated with passing through a planet's upper atmosphere. In-flight dispersions due to delivery errors, environment variables, and aerodynamic performance impose a large flight envelope. System studies for aerocapture often select high lift-to-drag ratios to compensate for these uncertainties. However, modern predictor-corrector guidance strategies have shown promise in recent years to provide robust control schemes in-situ. These algorithms do not rely on a pre-calculated reference trajectory and instead employ a numerical optimizer to continuously solve nonlinear equations of motion each guidance cycle. Numerical predictor-corrector strategies may provide considerable accuracy over heritage guidance schemes. The goal of this study is reproduce a landmark study of Neptune aerocapture and apply modern guidance to illustrate relative performance improvements and cost-saving potential. Capture constraints based on the theoretical corridor width are considered. Results indicate that heritage vehicles with moderate lift-to-drag ratios, lower than previous studies have indicated, may prove viable for aerocapture at Neptune. [View Full Paper]

* Graduate Research Assistant, University of Colorado Boulder, 431 UCB, Boulder, Colorado 80309, USA.
† Aerospace Engineer, NASA Langley Research Center, Atmospheric Flight and Entry Systems Branch, 1 N. Dryden Street, M/S 489, Hampton, Virginia 23681, USA.
‡ Dean of Engineering and Applied Science, University of Colorado Boulder, 429 UCB, Boulder, Colorado 80309, USA.

A DIRECT CHEBYSHEV PICARD ITERATION APPROACH TO PERTURBED BALLISTIC PROPAGATION AND LAMBERT BOUNDARY VALUE PROBLEMS

Chuck W. Wright[*]

Modified Chebyshev Picard Iteration (MCPI) combines Picard iteration with function approximation using Chebyshev series to numerically solve ordinary differential Equations. The MCPI method is an efficient means to solve perturbed orbital mechanics problems using a matrix formulation. This paper borrows elements of current MCPI methods but introduces a simplified approach which relies on direct integration of the Chebyshev polynomials themselves. Unlike other MCPI methods, the Direct Chebyshev Picard Iteration (DCPI) approach does not calculate separate polynomial series coefficients for each integral. It simply applies the original series coefficients to the integrated Chebyshev polynomials to form an invariant integral transformation matrix which may be applied to the accelerations to obtain the velocities. A similar matrix is applied to obtain a second integral for the position. Unlike other MCPI approaches this method uses exact analytical integrals of the original Chebyshev series with no least squares approximation. The boundary conditions are applied after the integrations to perform either a Lambert Boundary Value Problem (BVP), or a simple ballistic propagation Initial Value Problem (IVP) in much the same way that integration constants are determined when performing an integral by hand. This makes the overall approach relatively intuitive for anyone who is familiar with basic integral Calculus. While no direct comparison is made against the performance of other contemporary MCPI methods, the DCPI method accuracy is tested against fourth order Runge-Kutta using an 8x8 EGM 2008 gravity model for a variety of orbital trajectories ranging from Low Earth Orbit (LEO) to High Earth Orbit (HEO). The computational cost of generating a DCPI solution is shown to be much less than the Runge-Kutta method with accuracy on the order of 0.06 meters for a full LEO.

[View Full Paper]

[*] Principal Engineer, Simulation and GNC, Cummings Aerospace, Huntsville, Alabama 35806, USA.

USING GNSS RECEIVER AT NEAR RECTILINEAR HALO ORBIT

Yu Nakajima,* Toru Yamamoto† and Hitoshi Ikeda‡

This paper analyzes the feasibility of using a GPS receiver at Near Rectilinear Halo Orbit (NRHO). Given the longer distance between a GPS satellite and the receiver than that when using GPS on the ground, weak signals are obtained. Due to this characteristic, fewer satellites are tracked and used for navigation. However, those signals may be acquired by installing a high gain antenna with a narrow beam width tailored for NRHO. This paper presents the expected performance of the GPS receiver with Kalman filter-based orbit determination, and clarifies the measures to improve it. [View Full Paper]

* Researcher, Research and Development Directorate, JAXA, 2-1-1 Sengen, Tsukuba, Ibaraki, Japan.
† Senior Researcher, Research and Development Directorate, JAXA, 2-1-1 Sengen, Tsukuba, Ibaraki, Japan.
‡ Associate Senior Researcher, Research and Development Directorate, JAXA, 3-1-1 Yoshinodai, Chuo, Sagamihara, Kanagawa, Japan.

AAS 19-293

ADAPTIVE GUIDANCE WITH REINFORCEMENT META LEARNING

Brian Gaudet[*] and Richard Linares[†]

This paper proposes a novel adaptive guidance system developed using reinforcement meta learning with a recurrent policy and value function approximator. The use of recurrent network layers allows the deployed policy to adapt real time to environmental forces acting on the agent. We compare the performance of the DR/DV guidance law, an RL agent with a non-recurrent policy, and an RL agent with a recurrent policy in four difficult tasks with unknown but highly variable dynamics. These tasks include a safe Mars landing with random engine failure and a landing on an asteroid with unknown environmental dynamics. We also demonstrate the ability of a recurrent policy to navigate using only Doppler radar altimeter returns, thus integrating guidance and navigation.

[View Full Paper]

[*] Co-Founder, DeepAnalytX LLC, 1130 Swall Meadows Road, Bishop, California 93514, USA.

[†] Charles Stark Draper Assistant Professor, Department of Aeronautics and Astronautics, Massachusetts Institute of Technology, Cambridge, Massachusetts 02139, USA.

DRAG-FREE AND ATTITUDE CONTROL SYSTEM, LESSONS LEARNED FROM MICROSCOPE FLIGHT (2016-2018)

Pascal Prieur,[*] Stephanie Delavault,[†] Thomas Lienart,[‡] Manuel Rodrigues,[§] Bernard Foulon,[**] John Moyard,[††] Alain Robert[‡‡] and Pierre-Yves Guidotti[§§]

Microscope is a European mission dedicated to the test of the Equivalence Principle with an improved accuracy of 10^{-15}. The 300kg drag-free microsatellite has recently completed its 2-year flight. The Drag Free and Attitude Control System (DFACS) aimed at giving a pure gravitational motion to the scientific instrument. The drag-free performance demonstrated on Microscope is now by far the finest ever achieved on low Earth orbit: $<10^{-12}$ m/s^2 @Fep, three axes for up to 8 days. The attitude control is also very accurate; an original accelero-stellar hybridization finely performs the estimated attitude in order to fulfil the angular rate stability requirement ($<10^{-9}$ rad/s @Fep). The paper reports the main events happened during the mission and presents the DFACS behavior through the example of the session #256. Some end-of-life experiment are exposed, showing that the origin of spikes remains difficult to locate precisely. And a discussion is opened about the lessons learned from this mission. What could be a good DFACS design for Microscope II?
[View Full Paper]

[*] Flight Dynamics dept, CNES, 18 avenue Edouard Belin, F-31401 Toulouse, France.
[†] Flight Dynamics dept, CNES, 18 avenue Edouard Belin, F-31401 Toulouse, France.
[‡] Head of Propulsion dept, CNES, 18 avenue Edouard Belin, F-31401 Toulouse, France.
[§] TSAGE instr Project manager, ONERA, chemin de la Hunière, BP 80100, F-91123 Palaiseau cedex, France.
[**] Dept of Physics Instrumentation, ONERA, chemin de la Hunière, BP 80100, F-91123 Palaiseau cedex, France.
[††] Dept of Precise Orbit Determination, CNES, 18 avenue Edouard Belin, F-31401 Toulouse, France.
[‡‡] Dept of Fundamental physics missions, CNES, 18 avenue Edouard Belin, F-31401 Toulouse, France.
[§§] Dept of Fundamental physics missions, CNES, 18 avenue Edouard Belin, F-31401 Toulouse, France.

A NEW GUIDANCE AND CONTROL ARCHITECTURE FOR ACCURATE ORBIT INJECTION*

Mauro Pontani† and Fabio Celani‡

Accurate orbit injection represents a crucial issue in several mission scenarios, e.g. for spacecraft orbiting the Earth or for payload release from the upper stage of an ascent vehicle. This work considers a new guidance and control architecture based on the combined use of (i) the variable-time-domain neighboring optimal guidance technique (VTD-NOG), and (ii) the constrained proportional-derivative (CPD) algorithm for attitude control. More specifically, VTD-NOG & CPD is applied to two distinct injection maneuvers: (a) Hohmann-like finite-thrust transfer from a low Earth orbit to a geostationary orbit, and (b) orbit injection of the upper stage of a launch vehicle. Nonnominal flight conditions are modeled by assuming errors on the initial position, velocity, attitude, and attitude rate, as well as actuation deviations. Extensive Monte Carlo campaigns prove effectiveness and accuracy of the guidance and control methodology at hand, in the presence of realistic deviations from nominal flight conditions. [View Full Paper]

† Assistant Professor, Department of Astronautical, Electrical, and Energy Engineering, Sapienza University of Rome, via Salaria 851, 00138 Rome, Italy.

‡ Assistant Professor, School of Aerospace Engineering, Sapienza University of Rome, via Salaria 851, 00138 Rome, Italy.

DATA-DRIVEN MODEL-FREE ADAPTIVE SLIDING MODE ATTITUDE CONTROL OF COMBINED SPACECRAFT

Yueyong Lyu,* Zhaowei Sun,† Han Gao‡ and Yuhan Liu§

In this paper, a data-driven model-free adaptive sliding mode attitude control (MFASMC) method is proposed for the combined spacecraft in the presence of unknown mathematical model. First, a model-free adaptive controller (MFAC) is designed for the attitude control of combined spacecraft. Second, a sliding-mode-based supplementary controller is introduced to improve the tracking performance of MFAC in terms of robustness. Compared with the existing works, the designed control scheme only utilizes the attitude angle and attitude angular velocity of the combined spacecraft and no mechanism model of combined spacecraft is required. It dramatically decreases the complexity and difficulty of the relevant controller design. Finally, simulation comparison between the MFASMC and MFAC is given to verify the effectiveness of the proposed control method. [View Full Paper]

* Lecturer, Dept. of Control Science and Engineering, Harbin Institute of Technology, West Dazhi Street, No.92, Box.327, Room 616, Nan Gang District, Harbin, Heilongjiang 150001, China. (+86) 045186413411-8606.
E-mail: lvyy@hit.edu.cn.
† Professor, Dept. of Aerospace Science and Technology, Harbin Institute of Technology, West Dazhi Street, No.92, Box.327, Room 616, Nan Gang District, Harbin, Heilongjiang 150001, China. (+86) 045186402726.
E-mail: sunzhaowei@hit.edu.cn.
‡ Ph.D., Dept. of Control Science and Engineering, Harbin Institute of Technology, West Dazhi Street, No.92, Box.327, Room 606, Nan Gang District, Harbin, Heilongjiang 150001, China. (+86) 045186413411-8606.
E-mail: gaohhit@163.com.
§ Ph.D., Dept. of Control Science and Engineering, Harbin Institute of Technology, West Dazhi Street, No.92, Box.327, Room 606, Nan Gang District, Harbin, Heilongjiang 150001, China. (+86) 045186413411-8606.
E-mail: liuyh_hit@163.com.

AAS 19-315

NEW IMPROVEMENTS ON ATMOSPHERIC TRAJECTORY OPTIMIZATION OF A ROCKET REUSABLE FIRST STAGE WITH TURBO ENGINES

Eric Bourgeois,* Jérémie Hassin† and Nicolas Praly‡

Following paper 16-230, methodological improvements are presented to optimize the trajectory of a reusable micro-launcher first stage. The stage comes back to the launch site thanks to aerodynamics and turbo engines. Thrust characteristics of turbo-engines depend on flight conditions, and allow a wide thrust modulation: these features challenge methods to optimize rocket trajectory. Previously, two simplified methods were combined to benefit from their respective assets, this process allowing to ensure feasible trajectory, with no guaranty on optimality. Now is presented a method relying on optimal control theory taking into account a turbo-engine model defining relationships between flight conditions, thrust and fuel consumption. This study is performed in the frame of CNES Future Launcher Prospective Program. [View Full Paper]

* Trajectory Optimization, Navigation and Guidance Expert, "Safety, Performance & Control" Department, CNES - Launcher Directorate, 52 rue Jacques Hillairet, 75012 Paris, France.
† System Program Manager, "Future Launcher Prospective" Department, CNES - Launcher Directorate, 52 rue Jacques Hillairet, 75012 Paris, France.
‡ System Studies Expert, CS-SI, 22 avenue Galilée, 92350 Le Plessis Robinson, France.

AAS 19-351

AN ANALYSIS OF LOW-THRUST GUIDANCE ALGORITHMS AROUND SMALL BODIES

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

This paper examines the performance of low-thrust guidance algorithms (bi-linear tangent, Lambert, and cross-product guidance) around small bodies. Current small body missions (e.g. OSIRIS-Rex and Rosetta) use chemical thrusters which are inefficient for maneuvering in the microgravity environment around small bodies. When compared to impulsive propulsion systems, low-thrust propulsion provides a smaller force with greater efficiency while still maintaining a high control authority. By perturbing the initial conditions of a nominal trajectory, the performance of the guidance algorithms can be tested. It is hypothesized that these low-thrust guidance algorithms will provide accurate, mass-efficient, and robust guidance to a perturbed spacecraft trajectory around small bodies. [View Full Paper]

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

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

AAS 19-391

A GYROLESS ATTITUDE DETERMINATION APPROACH FOR SPACECRAFT BASED ON FACTOR GRAPH

Yongchao ZHAO,* Shijie ZHANG† and Botian ZHOU‡

Aiming at star tracker attitude determination in the absence of gyroscope, this paper proposes a gyroless attitude determination approach based on factor graph. We choose spacecraft attitude, angular velocity and spatial disturbance torque as the states. By using spacecraft dynamics, star tracker measurement equation and noise-driven spatial disturbance torque, the gyroless attitude determination factor graph is established to describe the relationships between states and the relationships between states and measurements of star tracker. The incremental characteristic of the factor graph is analyzed. For getting the optimal states, the factor graph is processed by incremental smoothing algorithm which could decrease computation complexity compared with Gauss-Newton algorithm. The mathematical simulation result shows that the proposed method can effectively realize the attitude determination in the absence of gyroscope. Our method can achieve more accurate attitude determination compared with EKF. [View Full Paper]

* Master Student, Research Center of Satellite Technology, Harbin Institute of Technology, 150001, Harbin, China.
† Professor, Research Center of Satellite Technology, Harbin Institute of Technology, 150001, Harbin, China.
‡ Ph.D. Student, Research Center of Satellite Technology, Harbin Institute of Technology, 150001, Harbin, China.

RECURSIVE MULTIPLICATIVE ESTIMATION OF RIGID BODY ATTITUDE AND MOMENT OF INERTIA

J. Cameron Helmuth,[*] Jacob E. Darling[†] and Kyle J. DeMars[‡]

Typically, the center of mass and inertia tensor of a spacecraft are estimated pre-launch using a mass properties table and/or a CAD model of the spacecraft. If these estimates are not sufficiently accurate to meet mission requirements, they can be refined after launch using sensor data from the spacecraft. In order to refine pre-launch estimates of these properties, variations of the Kalman filter are developed to estimate the attitude and angular rate of the spacecraft, as well as a representation of the inertia tensor. Two parametrizations of the inertia tensor are investigated: the standard moments and products of inertia representation and a representation formed from the principal moments of inertia and the attitude of the principal axes. Monte Carlo analysis is considered for three scenarios in which the mass properties are estimated, and it is shown that both methods are statistically consistent and capable of improving upon inertia estimates but suffer from linearization error when uncertainty in the moment of inertia tensor is large. [View Full Paper]

[*] Graduate Student, Department of Mechanical and Aerospace Engineering, Missouri University of Science and Technology, Rolla, Missouri 65409, USA.
[†] Research Aerospace Engineer, Air Force Research Laboratory, Space Vehicles Directorate, Kirtland AFB, New Mexico 87117, USA. AAS/AIAA Member.
[‡] Assistant Professor, Department of Mechanical and Aerospace Engineering, Missouri University of Science and Technology, Rolla, Missouri 65409, USA.

AAS 19-494

CENTROIDING PERFORMANCE FOR HORIZON-BASED OPTICAL NAVIGATION WITH CASSINI IMAGES OF DIONE AND RHEA

Courtney L. Hollenberg,* John A. Christian,†
Shyam Bhaskaran‡ and William M. Owen§

Optical navigation (OPNAV) is a key enabling technology for space science missions beyond low Earth orbit. Horizon-based OPNAV methods involve image processing on the lit limb of a resolved celestial body in order to generate a bearing measurement to the body center. In recent work, the authors introduced a new horizon-based technique that combines an improved subpixel edge localization method with a non-iterative solution for spacecraft position relative to an ellipsoidal body. In this work, the performance of the new technique applied to OPNAV images of the Saturnian satellites Dione and Rhea from the Cassini spacecraft is evaluated against the ground truth mission data. Image plane centroid estimates from the new method are compared to the legacy centerfinding results produced by JPL in support of the Cassini mission, which were computed via an iterative limb-scan technique. Additionally, kinematic position residuals are presented for the full mission span. [View Full Paper]

* Graduate Research Assistant, Department of Mechanical, Aerospace, and Nuclear Engineering, Rensselaer Polytechnic Institute, Troy, New York 12180, USA.
† Assistant Professor, Department of Mechanical, Aerospace, and Nuclear Engineering, Rensselaer Polytechnic Institute, Troy, New York 12180, USA.
‡ Supervisor, Outer Planet Navigation Group, Jet Propulsion Laboratory, California Institute of Technology, Pasadena, California 91109, USA.
§ Mission Design and Navigation Section, Jet Propulsion Laboratory, California Institute of Technology, Pasadena, California 91109, USA.

AAS 19-522

COORDINATION OF A DECENTRALIZED SATELLITE SWARM WITH INTERNAL FORMATION

John McCormack[*] and May-Win Thein[†]

In this paper, the authors propose the use of an Artificial Potential Field (APF), previously used for the control and coordination of multiple agents through the use of Sliding Mode Control (SMC), to be used for the control and coordination of individual spacecraft in constellation/swarm missions. The APF is shown to satisfy necessary conditions for a given proof of stability: more specifically, stability for boundedness and equilibrium locations. Artificial attractive nodes are introduced to create a decentralized spacecraft swarm capable for aggregating a formation with additional agents present. Gain ranges for the APF equation ensure that individual spacecraft agents maintain proper "safe distance". Numerical simulations are presented to demonstrate the proposed swarm coordination control technique. [View Full Paper]

[*] Graduate Student, Mechanical Engineering, University of New Hampshire, Durham, New Hampshire 03824, USA. E-mail: jmz345@wildcats.unh.edu.

[†] Associate Professor, Mechanical Engineering, University of New Hampshire, Durham, New Hampshire 03824, USA. E-mail: may-win.thein@unh.edu.

INTEGRATED TARGETING, GUIDANCE, NAVIGATION, AND CONTROL FOR UNMANNED AERIAL VEHICLES

Evan Kawamura[*] and Dilmurat Azimov[†]

This study aims to develop targeting, guidance, navigation, and control functions and their integration for applications. Due to its simplicity and accessibility, the INAV software has been selected as a framework for the proposed integration. It is shown that the proposed study changes the current PID control laws and the utility of new nonlinear control schemes allow us to leverage the flight autonomy thereby paving the way for creating an autonomous control technology with real-time target-relative guidance capabilities. An illustrative example is considered to demonstrate the utility of guidance, navigation, and control functions in INAV to perform a rolling maneuver. [View Full Paper]

[*] PhD Student, Mechanical Engineering, University of Hawaii at Manoa, 2540 Dole Street, Holmes 302, Honolulu, Hawaii 96822, USA.

[†] Associate Professor, Mechanical Engineering, University of Hawaii at Manoa, 2540 Dole Street, Holmes 202A, Honolulu, Hawaiii 96822, USA.

MODEL-BASED OPTICAL NAVIGATION FOR AUTONOMOUS LANDING ON ASTEROIDS

Yuki Takao,[*] Yuichi Tsuda,[†] Takanao Saiki[‡] and Naoko Ogawa[§]

An optical navigation method for autonomous landing on asteroids using asteroid shape model is presented. Vertices of the shape model are tracked in the sequential images obtained by a monocular camera. The proposed method does not need the process of landmark detection or mapping. The pose of the spacecraft is estimated using particle filter, considering the dynamics around the asteroid. The performance of the developed navigation method is evaluated via numerical simulation; it is based on the touchdown rehearsal operation in Hayabusa2 Mission to show the effectiveness of the proposed method against actual asteroid exploration missions. [View Full Paper]

[*] Ph.D. Student, Department of Aeronautics and Astronautics, The University of Tokyo, 7-3-1 Hongo, Bunkyo-ku, Tokyo, 113-8654, Japan.
[†] Associate Professor, Department of Space Flight Systems, Institute of Space and Astronautical Science, Japan Aerospace Exploration Agency, 3-1-1 Yoshinodai, Chuo-ku, Sagamihara, Kanagawa, 252-5210, Japan.
[‡] Assistant Professor, Department of Space Flight Systems, Institute of Space and Astronautical Science, Japan Aerospace Exploration Agency, 3-1-1 Yoshinodai, Chuo-ku, Sagamihara, Kanagawa, 252-5210, Japan.
[§] Engineer, Hayabusa2 Project Team, Institute of Space and Astronautical Science, Japan Aerospace Exploration Agency, 3-1-1 Yoshinodai, Chuo-ku, Sagamihara, Kanagawa, 252-5210, Japan.

AAS 19-574

A REAL-TIME GNC FRAMEWORK FOR RENDEZVOUS OF SMALL SATELLITES IN A UNIFORM GRAVITATIONAL FIELD

Jonathan De Leon*

With the use of small satellites on the rise as a cheap alternative to conventional satellites, there is a rising need for autonomous solutions for their maneuvers. The purpose of this research is to generate a real time analytical solution for rendezvous of small satellites in a uniform gravitational field using constant thrust and create a Guidance Navigation and Control (GNC) solution for this rendezvous problem. This analytical solution will make computations less expensive than the current numerical methods that are in use. This analytical solution is used in a GNC framework to create real-time solutions that are used in the autonomy of the small satellite. [View Full Paper]

* B.S. Mechanical Engineering student at University of Hawaii at Manoa, Honolulu, Hawaii 96822, USA.

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