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Front Cover Illustration:

Artist concept of NASA's New Horizons reaching its historic encounter on July 14, 2015 after its three-billion-mile journey to Pluto and its moons. The spacecraft's suite of seven science instruments—which includes cameras, spectrometers, and plasma and dust detectors—will map the geology of Pluto and Charon and map their surface compositions and temperatures; examine Pluto's atmosphere, and search for an atmosphere around Charon; study Pluto's smaller satellites; and look for rings and additional satellites around Pluto. Photo Credit: NASA / Johns Hopkins University Applied Physics Laboratory / Southwest Research Institute.

American Astronautical Society

ASTRODYNAMICS 2015

Volume 156

ADVANCES IN THE ASTRONAUTICAL SCIENCES

Edited by
Manoranjan Majji
James D. Turner
Geoff G. Wawrzyniak
William Todd Cerven

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FOREWORD

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

Astrodynamics 2015, Volume 156, Advances in the Astronautical Sciences, consists of four parts totaling about 4,500 pages, plus a CD ROM which contains all the available papers in digital format. Papers which were not available for publication are listed on the divider pages of each section in the hard copy volume and in the main linking file of the digital version of the volume. A chronological numerical index and an author index appear at the end of the main linking file, and are appended to the fourth part of the volume.

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

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

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

AAS/AIAA ASTRODYNAMICS VOLUMES

Astrodynamics 2015 appears as Volume 156, *Advances in the Astronautical Sciences*. This publication presents the complete proceedings of the AAS/AIAA Astrodynamics Conference 2015.

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

AAS/AIAA SPACEFLIGHT MECHANICS VOLUMES

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

Spaceflight Mechanics 2014, Volume 152, *Advances in the Astronautical Sciences*, Eds. Roby 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*).

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Robert H. Jacobs, Series Editor

PREFACE

The 2015 AAS/AIAA Astrodynamics Specialist Conference was held at the Vail Cascade Resort, Vail, Colorado between August 11–13, 2015. 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 260 people registered for the meeting; attendees included engineers, scientists, and mathematicians representing government agencies, the military services, industry, and academia from the United States and abroad.

There were 254 technical papers presented in 28 sessions on topics related to space-flight mechanics and astrodynamics. The special sessions on Space Situational Awareness, Asteroid and Non-Earth Orbiting Missions, High Performance Computing and Space Missions: New Horizons MESSENGER and Mars Reconnaissance Orbiter were well received and strongly attended. The meeting included various social events, including the welcome reception on Sunday, August 9, and the Awards Banquet on Tuesday, August 11, 2015.

The editors extend their gratitude to the Session Chairs who made this meeting successful: Ossama Abdelkhalik, Maruthi Akella, Nitin Arora, Brent Barbee, Angela Bowes, Jonathan Brown, Thomas Carter, Suman Chakravorty, Kyle DeMars, Atri Dutta, Carolin Frueh, Kohei Fujimoto, Rees Fullmer, Roberto Furfaro, Liam Healy, Marcus Holzinger, Felix Hoots, Kathleen Howell, Islam Hussein, David Hyland, Simon Julier, Mark Karpenko, Daniel Litton, Alfred Lynam, James McAdams, Craig McLaughlin, Jay McMahon, Robert Melton, Jeff Parker, Glenn Peterson, Minh Phan, Marcin Pilinski, Christopher Roscoe, Ryan Russell, Hanspeter Schaub, David Spencer, Christopher Spreen, Thomas Starchville, Nathan Strange, Jeffrey Stuart, Sergei Tanygin, Srinivas R. Vadali, David Vallado, Ryan Weisman, Bong Wie, Bobby Williams, Jacob Williams, Roby Wilson, Renato Zanetti. Our gratitude also goes to Felix Hoots, Kathleen Howell and Puneet Singla for their guidance, support and assistance in the successful organization of the conference.

Dr. Manoranjan Majji **AAS Technical Chair**	**Dr. Geoff G. Wawrzyniak** **AAS General Chair**
Dr. James D. Turner **AIAA Technical Chair**	**Dr. William Todd Cerven** **AIAA General Chair**

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Part IV

SPACE SITUATIONAL AWARENESS

Session Chairs:

Simon Julier, University College London
Islam Hussein, Applied Defense Solutions
David Vallado, Center for Space Standards and Innovation
Ryan Weisman, Air Force Research Laboratory
Marcus Holzinger, Georgia Institute of Technology

The following papers were not available for publication:

AAS 15-578	Paper Withdrawn
AAS 15-676	Paper Withdrawn
AAS 15-763	Paper Withdrawn

AAS 15-500

NEW CONSOLIDATED FILES FOR EARTH ORIENTATION PARAMETERS AND SPACE WEATHER DATA

David A. Vallado* **and TS. Kelso†**

Earth Orientation Parameter (EOP) and Space Weather data are critical data elements for numerical propagation and space operations. Since CSSI first began assembling consolidated files of EOP and space weather data in 2005, we have continually sought to improve the accuracy of that process. A recent effort reexamined all the sources and added additional logic to permit quick estimation of long range solar cycle values and providing missing indices where they could be reliably estimated. This paper provides detailed documentation concerning the assembly and rationale for choices made as well as accuracy plots for predicted values.

[View Full Paper]

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AAS 15-537

UPDATED ANALYTICAL PARTIALS FOR COVARIANCE TRANSFORMATIONS AND OPTIMIZATION

David A. Vallado* **and Salvatore Alfano†**

Covariance estimates are becoming more widely available as flight dynamics operations work towards greater accuracy. Investigators have looked at how covariance matrices are propagated, to include orbital state formats and coordinate systems. Various equations to convert between orbital state formats and satellite coordinate systems are essential for proper use and analysis. The literature contains many examples. Vallado (2003) presented a complete set of equations, but advised that a few inconsistencies were found. We have corrected those errors and provide the results. Test results are given for several cases, and MatLab code is available.

[View Full Paper]

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AAS 15-539

ANGLES-ONLY ALGORITHMS FOR INITIAL ORBIT DETERMINATION REVISITED

Gim J. Der[*]

This paper presents numerical results to address the historical questions:

1. How accurate was the 1801 Ceres data of Piazzi?
2. Did Laplace compute any Ceres orbit?
3. How accurate was the 1801 Ceres orbit computed by Gauss?
4. Why the angle-only problem remains a great challenge over 200 years?

This author's 2012 AMOS paper provided 10 numerical examples and marked a new range-solving angles-only algorithm that can consistently determine the correct range and initial perturbed orbit of any unknown object in all orbit regimes without guessing. This new algorithm allows optical sensors to be used for efficient and cost-effective catalog maintenance and catalog building.

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AAS 15-555

UPDATING POSITION DATA FROM UNBOUNDED SERENDIPITOUS SATELLITE STREAKS[*]

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

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

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AAS 15-571

BOUNDING COLLISION PROBABILITY UPDATES

William Todd Cerven[*]

Over the last couple of decades, the probability of collision (Pc) has been established as the dominant metric for evaluating satellite close approaches. However, the use of Pc by decision-makers has been limited due at least partially to its non-intuitive and often wild variations between catalog updates. It simply does not show the same consistency that relative miss geometry updates show relative to predicted uncertainties. This paper presents a method for predictively computing probabilities and confidence bounds on how the Pc will change with an update.

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GAUSSIAN MIXTURE APPROXIMATION OF THE BEARINGS-ONLY INITIAL ORBIT DETERMINATION LIKELIHOOD FUNCTION

Mark L. Psiaki,[*] Ryan M. Weisman[†] and Moriba K. Jah[‡]

A method is developed to approximate the bearings-only orbit determination likelihood function using a Gaussian mixture to incorporate information about an admissible region. The resulting probability density function can provide the *a priori* information for a Gaussian mixture orbit determination filter. The new technique starts with a nonlinear batch least-squares solution. The solution enforces soft constraints on an admissible region defined in terms of minimum periapsis and maximum apoapsis. This admissible region information can compensate for poor observability from a short arc of bearings-only data. Although this soft-constrained solution lies in or near the admissible region, it does not characterize that region well. It provides a starting point to develop a Gaussian mixture approximation of the batch least-squares likelihood function as modified through multiplication by a finite-support function that is zero outside the admissible region and equal to one in that region. This Gaussian mixture is optimized to fit the resulting probability density in the 2-dimensional subspace of position/velocity space that has the most uncertainty. This optimal fitting allows the Gaussian mixture to use a low number of mixands while fitting the finite-support probability density function well. By approximating the product of a finite-support function and the original likelihood function, the new method gains the capability to transition smoothly between regimes where the admissibility constraints dominate, i.e., high-altitude/short-measurement-arc cases, and those where they are irrelevant, i.e., low-altitude/long-measurement-arc cases.

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AAS 15-577

THE PROBABILISTIC ADMISSIBLE REGION WITH ADDITIONAL CONSTRAINTS[*]

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

The admissible region is defined as the set of physically acceptable orbits (i.e., orbits with negative energies). Given additional constraints on orbital semimajor axis, eccentricity, etc., the admissible region is further constrained, resulting in the constrained admissible region (CAR). Based on known statistics of the measurement process, the hard constraints are replaced by a probabilistic representation. This results in the probabilistic admissible region (PAR), which can be used for orbit initiation in Bayesian tracking. Additional constraints are incorporated, by considering some given statistics over inclination and right ascension of the ascending node. This results in a four-dimensional PAR distribution. Noting that the concepts presented are general and can be applied to any measurement scenario, the idea is illustrated using a short-arc, angles-only observation scenario.

[View Full Paper]

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AAS 15-579

COLLISION RISK METRICS FOR LARGE DISPERSION CLOUDS DURING THE LAUNCH COLA GAP[*]

Alan B. Jenkin[†]

Standard launch collision avoidance (COLA) methods are based on ellipsoidal and Gaussian models of the position dispersion clouds of launched objects such as upper stages and payload satellites. During the COLA gap, which is the time interval between the end of the launch COLA screening and the start of on-orbit COLA screening, the dispersion clouds can become very large, non-ellipsoidal, and non-Gaussian. A method for computing collision risk metrics during the COLA gap based on kernel density estimation has been developed. The method enables the determination of a smooth analytical representation of the distribution of conjunctions from a Monte Carlo representation of the dispersion cloud. This enables the use of detailed launch vehicle simulation results and avoids the need to make assumptions on the dispersion cloud distribution. Two COLA gap metrics are computed: containment inside the dispersion cloud and probability of collision. The basic theory behind the method is first discussed. Results are then presented for sample launch cases, including variation of dispersion cloud containment and collision probability with time and launch window opportunity. Sensitivity of the metrics to the number of Monte Carlo points and screening volume is determined.

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AAS 15-581

VOLUMETRIC ENCOUNTER ANALYSIS ENHANCEMENTS

Salvatore Alfano[*] and Daniel Oltrogge[†]

Presented here is an improved planning and characterization tool that can be used to estimate the satellite encounter operational tempo for a given orbit against a satellite catalog. The spherical encounter volume in our original work is replaced with an ellipsoid that is constant in size, shape, and orientation in the satellite's Radial-InTrack-CrossTrack frame. For a given pair of satellites we accomplish this by defining a traveling ellipsoid about the second satellite's orbit and assessing if/when the first satellite's orbit traverses it. To ensure that no encounter is missed, the ellipsoid is moved along the second satellite's circular or elliptical orbit in increments of true anomaly corresponding to intrack movement much smaller than the ellipsoid's minor axis. An incremental determination of encounter probability is made if/when the first satellite's orbit track contacts the ellipsoid. When this takes place, the orbit true anomalies extant at ellipsoid entry and exit are captured for both satellites and converted to their respective mean anomaly ranges. The likelihood that both satellites will simultaneously be inside that encounter region is then determined from these ranges. In addition to determining probability, the method also estimates the number of expected encounters over a given time span. The method is valid for both coplanar and non-coplanar orbits. However, our assumption of uniformly distributed relative in-track positions is not applicable in all satellite pairings. This method is useful in identifying such regions as graveyard orbits that are least likely to produce encounters. It can also be used to estimate how often neighboring satellites will trigger volumetric warnings when considering a candidate orbit. We make a limited version of this tool publicly available through a non-subscriber website Graphical User Interface, where only spherical encounter regions in LEO circular orbits are considered.

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TRACK-TO-TRACK ASSOCIATION USING INFORMATION THEORETIC CRITERIA[*]

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

There are three primary types of data association problems of interest in space surveillance: the observation-to-track association (OTTA) problem, the track-to-track association (TTTA) problem, and the observation-to-observation association (OTOA) problem. In this paper, we build on recent work to further investigate the use of information theoretic criteria to solve the TTTA problem, in which we have multiple uncorrelated tracks (UCTs) to be tested for association against a given set of tracks given at a different (usually previous) time instance. Both the tracks and the UCTs are uncertain and are probabilistically described using multivariate normal distributions. This allows for a closed-form solution based on the unscented transform and on information divergence for Gaussian distributions. We will establish relationship to the covariance-based track association (CBTA) technique and compare the performance of the two methods in Monte Carlo simulations.

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AAS 15-639

MINIMIZATION OF THE KULLBACK-LEIBLER DIVERGENCE FOR NONLINEAR ESTIMATION

Jacob E. Darling[*] **and Kyle J. DeMars**[†]

A nonlinear approximate Bayesian filter, named the minimum divergence filter (MDF), is proposed in which the true state density is approximated by an assumed density. The parameters of the assumed density are found by minimizing the Kullback-Leibler divergence of the assumed density with respect to the true density that is defined by either the Chapman-Kolmogorov equation or Bayes' Rule for the predictor and corrector steps, respectively. When an assumed Gaussian density is used and the system dynamics and measurement model possess additive Gaussian-distributed noise, the predictor of the MDF is identical to the predictor used under the Kalman framework, and the corrector defines the mean and covariance of the posterior Gaussian density as the first and second central moments of the posterior defined by Bayes' Rule. Because the MDF works for arbitrary densities, it can also quantify the temporal and measurement evolution of the parameters of an assumed directional state density. Simulations are shown to compare the MDF to standard Kalman-type filters, as well as the ability of the MDF to correct the parameters of an assumed Gauss-Bingham density given a von Mises-distributed line-of-sight measurement.

[View Full Paper]

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AAS 15-648

ANALYSIS AND COMPARISON ON UKF AND BLS FOR ORBIT DETERMINATION

Lu Deng,[*] Xiucong Sun[†] and Chao Han[‡]

Based on BeiDou-2 constellation navigation, properties of a relatively new method, unscented Kalman filter and the most classical method, batch least squares method are discussed. First, the research progresses of these two estimation methods are summarized, and then the principles of unscented Kalman filter and batch least squares method are briefly reviewed. Sensitivity analysis of orbit determination results to different measurement errors, measurement data-sampling periods, and dynamic model errors, are made with classical unscented Kalman filter and batch least squares method. By comparison n, conclusions are drawn about choice of estimation method in constellation navigation.

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IMPROVING GEOLOCATION ACCURACY THROUGH REFINED SATELLITE EPHEMERIS ESTIMATION IN AN ILL-CONDITIONED SYSTEM

Jeroen L. Geeraert,[*] Brandon A. Jones[†] and Jay W. McMahon[†]

Commercial geolocating systems claim a capability of estimating the position of an Earth-based signal to within 5 km. Ephemeris inaccuracies are generally the primary source of error in geolocation and is therefore a main focus of this paper. Using a two-satellite technique of time difference of arrival (TDOA), frequency difference of arrival (FDOA), and an improved ephemeris estimate, we are able to show geolocating capabilities down to several hundred meters using real data. High fidelity dynamic and measurement models are used with both a batch and a square root information filter (SRIF) in a two-step process. First, using known calibrator transmitters, the ephemeris is estimated. Second, using this ephemeris an unknown transmitter is geolocated with a consider batch filter (CBF). Due to the geometry of the satellite, transmitter and receiver setup, however, the system is ill-conditioned and introduces sensitivities, especially in the ballistic coefficient type parameters representative of solar radiation pressure (SRP). In spite of those sensitivities, the reduced ephemeris error significantly improves the geolocation accuracy.

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AAS 15-673

A CORRECTNESS RATIO METRIC FOR ASSESSING DATA ASSOCIATION METHODS IN SPACE SURVEILLANCE[*]

Joshua T. Horwood,[†] Jeffrey M. Aristoff,[‡] David J. C. Beach,[§]
P. Alex Ferris,[**] Alex D. Mont,[**] Navraj Singh[**] and Aubrey B. Poore[††]

This paper describes a metric for assessing the performance of data association methods used in space surveillance tracking systems that facilitates regression testing, benchmark trade studies, and comparisons between the many different paradigms for data association brought forth by the community. The proposed correctness ratio metric gives a macro perspective on how a tracking system is performing, provides an honest assessment of performance since it penalizes both for incorrectly associated observations (cross-tags) as well as for missing observations, and streamlines the communication of results and performance to decision makers.

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AAS 15-675

MULTIPLE FRAME ASSIGNMENT SPACE TRACKER (MFAST): RESULTS ON UCT PROCESSING[*]

**Jeffrey M. Aristoff,[†] David J. C. Beach,[‡] P. Alex Ferris,[§]
Joshua T. Horwood,[**] Alex D. Mont,[**] Navraj Singh[**] and Aubrey B. Poore[††]**

Numerica's Multiple Frame Assignment Space Tracker (MFAST) is a multi-sensor multi-regime space object tracking system that is presently undergoing transition to an operational environment to support improved uncorrelated track (UCT) processing. This paper communicates recent results from MFAST that were obtained by processing real-world historical radar and optical data from the Space Surveillance Network (SSN) in a "UCT processing mode." The results demonstrate that MFAST generally achieves a correctness ratio of 93% or higher, with no cross-tags, and is able to process the data on a consumer-grade laptop computer in real-time or faster.

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AAS 15-717

AN UPPER BOUND ON HIGH SPEED SATELLITE COLLISION PROBABILITY WHEN ONLY ONE OBJECT HAS POSITION UNCERTAINTY INFORMATION

Joseph H. Frisbee, Jr.[*]

Upper bounds on high speed satellite collision probability, P_C, have been investigated. Previous methods assume an individual position error covariance matrix is available for each object. The two matrices being combined into a single, relative position error covariance matrix. Components of the combined error covariance are then varied to obtain a maximum P_C. If error covariance information for only one of the two objects was available, either some default shape has been used or nothing could be done. An alternative is presented that uses the known covariance information along with a critical value of the missing covariance to obtain an approximate but potentially useful P_c upper bound.

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INITIAL RELATIVE ORBIT DETERMINATION ANALYTICAL ERROR COVARIANCE AND PERFORMANCE ANALYSIS FOR PROXIMITY OPERATIONS

Baichun Gong,[*] David K. Geller[†] and Jianjun Luo[‡]

This research furthers the development of a closed-form solution to the angles-only initial relative orbit determination problem for close-in proximity operations when the camera offset from the vehicle center-of-mass allows for range observability. Emphasis is placed on developing closed-form error covariance equations for the initial relative orbit state solution and verification of the analytic covariance equations through systematic nonlinear Monte Carlo simulation of typical rendezvous missions with the International Space Station. Closed-form analytic estimates of the relative state error covariance based on angle measurement errors, attitude knowledge errors and camera center-of-mass offset uncertainties for three and more observations are obtained. A two-body Monte Carlo simulation system is used to evaluate the performance of the closed-form relative state estimation algorithms and associated closed-form covariance equations. The sensitivity of the solution accuracy to spacecraft trajectories, camera offset, camera accuracy, attitude knowledge, and the time-interval between measurements is presented and discussed.

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AAS 15-725

REALISTIC COVARIANCE GENERATION IN THE PRESENCE OF MANEUVERS

Travis Lechtenberg,[*] Joshua Wysack,[†] Syed Hasan[‡] and William Guit[§]

Operational collision threat characterization is now an essential component of space mission operations. As the size of the space object catalog increases, more sophisticated collision threat characterization and collision avoidance strategies must be implemented. In order to accurately characterize collision risk, a realistic covariance must be used when computing collision probability. In order to generate realistic covariance, expected maneuver performance must be incorporated while modelling the spacecraft's predicted state uncertainty. This paper describes an approach for generating realistic predictive covariance for NASA's Earth Science Mission Operations (ESMO) satellite fleet.

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AAS 15-726

ORBIT DETERMINATION FOR PARTIALLY UNDERSTOOD OBJECT VIA MATCHED FILTER BANK

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

With knowledge of a space object's orbit, the matched filter is an image processing technique which allows low signal-to-noise ratio objects to be detected. Many space situational awareness research efforts have looked at ways to characterize the probability density function of a partially understood space object. When prior knowledge is only constrained to a probability density function, many matched filter templates could be representative of the space object, necessitating a bank of matched filters. This paper develops the measurement dissimilarity metric which is then applied to partition a general prior set of orbits. A method for hypothesis testing the result of a matched filter for a space object is developed. Finally, a framework for orbit determination based on the matched filter result is developed. Simulation shows that the analytic results enable more efficient computation and a better framework for implementing matched filters.

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AAS 15-730

EFFICIENT TRAJECTORY PROPAGATION FOR ORBIT DETERMINATION PROBLEMS

Javier Roa[*] **and Jesús Peláez**[†]

Regularized formulations of orbital motion apply a series of techniques to improve the numerical integration of the orbit. Despite their advantages and potential applications little attention has been paid to the propagation of the partial derivatives of the corresponding set of elements or coordinates, required in many orbit-determination scenarios and optimization problems. This paper fills this gap by presenting the general procedure for integrating the state-transition matrix of the system together with the nominal trajectory using regularized formulations and different sets of elements. The main difficulty comes from introducing an independent variable different from time, because the solution needs to be synchronized. The correction of the time delay is treated from a generic perspective not focused on any particular formulation. The synchronization using time-elements is also discussed. Numerical examples include strongly-perturbed orbits in the Pluto system, motivated by the recent flyby of the New Horizons spacecraft, together with a geocentric flyby of the NEAR spacecraft.

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AAS 15-733

PROBABILITY DENSITY TRANSFORMATIONS ON ADMISSIBLE REGIONS FOR DYNAMICAL SYSTEMS

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

The admissible region as used for initial orbit determination is often expressed as a uniform multivariate probability density function (PDF). A multivariate PDF may be transformed and expressed in an alternate state space if the total probability is preserved over the transformation. This paper applies the general multivariate PDF transformation method to an admissible region to develop the conditions required for such a transformation. Because the probability must be preserved, it is shown that in general an admissible region PDF may not be transformed by a nonlinear transformation unless specific mapping conditions are met over all the state space volume. If this condition is not met then the transformation of an admissible region PDF yields incorrect probabilities over the state space. Further, it is also shown that if each state in an admissible region is locally observable then the constant gradient condition is lifted.

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AAS 15-738

UNCUED SATELLITE INITIAL ORBIT DETERMINATION USING SIGNALS OF OPPORTUNITY

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

This paper investigates the application of signal of opportunity based multilateration to generate initial orbit estimates. Using at least 4 observer stations, the time differential of arrival of signals of opportunity can be measured and used to determine a 3D position estimate of the source of the signal with some associated covariance on the position estimate. While this solution gives the position of the object, admissible region theory may be applied to bound the possible velocity states belonging to a particular source. Two constraints are considered and analytically derived for the time differential of arrival problem to constraint the possible velocity solutions for a given position estimate. Once a joint admissible region is formed from these constraints, it may be sampled and used as an initial distribution for a particle filter. This work shows an example application of particle filter initiation with a time differential of arrival measurement based admissible region.

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ORBIT DETERMINATION FOR GEOSYNCHRONOUS SPACECRAFT ACROSS UNOBSERVED STATION-KEEPING MANEUVERS

Bryan C. Brown[*]

Accurately determining the orbits of geosynchronous spacecraft is challenging at best, and is even more difficult when such a spacecraft undergoes a station-keeping maneuver during which no observations are taken. Often even the times and kind of maneuver are unknown (apse pair, node pair, hybrid, etc.), except in the spacecraft operations center. Even so, it is often desirable to be able to include both pre-maneuver and post-maneuver observations in the orbit determination process. We discuss one method for modeling and using such maneuver models in batch Weighted Least Squares orbit determination.

Section 1 is an introduction and overview of the problem.

Section 2 presents the concept of operations used in the investigation.

Section 3 discusses the ad hoc maneuver model. The model requires accurate pre- and post-maneuver state vectors and masses, as well as ignition and burnout times and convergence parameters, and generates a table of maneuver accelerations and masses. Note that the process is not applicable to near real time operations because of the input requirements.

Section 4 discusses the enhancements to the Naval Research Laboratory's Orbit Covariance and Error ANalysis (OCEAN) orbit determination tool to use the maneuver model. OCEAN solves for the usual state vector parameters as well as one scale factor for each component of the table of maneuver accelerations.

Section 5 discusses the preliminary results. The errors in topocentric position are typically reduced from scores of millidegrees (without modeling the maneuver) to one or two millidegrees (often better) across the data arc.

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AAS 15-752

ON COMPARING PRECISION ORBIT SOLUTIONS OF GEODETIC SATELLITES GIVEN SEVERAL ATMOSPHERIC DENSITY MODELS

John G. Warner* **and Krysta M. Lemm***

Many aspects of a satellite mission are directly impacted by the ability to precisely determine and accurately predict the satellite's orbit through high precision orbit determination. While gravity forces are typically well understood, the modeling of non-conservative forces to a high precision, which is critical to high precision orbit determination of satellites in low Earth orbit, is often more challenging. A number of current and historically recommended atmospheric density models are examined using the Naval Research Laboratory's Orbit Covariance Estimation and ANalysis (OCEAN) tool. High precision laser ranging data to geodetic satellites were used as test cases to evaluate the solution accuracy and predictive capabilities of the atmospheric density models. Orbit fit and prediction comparison metrics are generated for multiple atmospheric density models. Generally, the Jacchia-Bowman 2008 model results in predictive orbit solutions that more closely follow the definitive orbit solution over the entire 30 day prediction span. Surprisingly, the exponential atmospheric density model, while the simplest model, preforms almost as well over the first ten days of orbit prediction.

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AAS 15-767

SENSOR BIAS ESTIMATION AND UNCERTAINTY QUANTIFICATION STRATEGIES FOR SPACE OBJECT TRACKING

Eamonn J. Moyer,* Ryan M. Weisman† and Manoranjan Majji‡

Measurements from any given sensor are corrupted by noise and are biased. The problems of estimation and uncertainty quantification of sensor biases are investigated in this paper. Several approaches to these problems are explored, and their success in the mitigation of bias is investigated. Filtering without compensating for bias, augmented filtering, and consider filtering approaches are studied and their results are compared. In addition, smoothing results are presented. The approaches have their own merits and drawbacks, and their pros and cons are discussed within and recommendations are made as to when to use which approach. Statistical consistency checks are provided to show when the filter is not performing as desired. The focus of this paper is on estimating biases that are assumed to be constant, but biases with a time varying structure can be accommodated if a sampling rate higher than the Nyquist frequency is available.

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OBTAINING NAVIGATION OBSERVABLES FROM HIGH DEFINITION TELEVISION TOWERS

Ryan E. Handzo,[*] Austin Anderson,[†] Jorge Cervantes,[‡] Jeffrey S. Parker,[§]
Dirk Grunwald[**] and George H. Born[††]

This paper considers the navigation observables that can be obtained from HDTV signals using the ATSC transmission standard. The ATSC transmission standard has multiple components that allow for range and Doppler navigation observables to be extracted. This paper looks at the structure of these observables as well as the types of hardware that are needed to obtain these observations. In addition, the paper will present a comparison between simulated signal data used in satellite navigation studies and real data collected using hardware on the ground.

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AAS 15-778

CHARACTERIZING THE EFFECTS OF LOW ORDER PERTURBATIONS ON GEODETIC SATELLITE PRECISION ORBIT DETERMINATION

Eric Eiler[*] and John G. Warner[†]

Satellite operations often rely on the ability to precisely determine and accurately predict the satellite's orbit. Thus, there are numerous papers dedicated to developing methodologies for successful orbit determination. However, there are also lower order forces that act upon satellites that are not directly studied in detail. Two such phenomenon are studied here; perturbations due to the Lunar geopotential, and lower order relativistic corrections. The effects of both on orbit determination are studied with US Naval Research Laboratory's Orbit Covariance Estimation and ANalysis (OCEAN) tool. High precision laser ranging data of geodetic satellites are used as test cases to evaluate the solution accuracy and predictive capabilities. Orbit fit quality and prediction comparison metrics are generated for a number of lunar gravity field models, as well as including or excluding several lower order relativistic corrections. Recommendations are made based on the results.

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AAS 15-780

THE IMPACT OF INTERSATELLITE RANGE MEASUREMENTS ON THE ORBIT DETERMINATION OF SATELLITE CONSTELLATIONS

Byron T. Davis[*] and Brian C. Gunter[†]

For many satellite remote sensing and communications applications, particularly those involving a formation or constellation of satellites, having precise knowledge of the satellite's position in both an absolute and relative sense is essential. With this in mind, this study examines potential gains in precise orbit determination (POD) when additional intersatellite range observations are combined with standard Global Navigation Satellite System (GNSS) observations. The methodology behind the combination approach is described and illustrated through a series of simulated case studies involving two or more satellites in low Earth orbit, using realistic assumptions on measurement noise. The results suggest that substantial improvements in the POD for all satellites in the constellation can be obtained with even intermittent ranging measurements. In addition, the precision of the intersatellite ranging measurements were limited to 1 mm or higher, with additional constraints on the intersatellite range distance, to represent levels possible from a nanosatelilte (cubesat) platform. By improving the positioning capabilities of cubesat constellations, new Earth observing missions utilizing cubesatellite constellation architectures will become feasible.

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AAS 15-807

INTERPLANETARY ORBIT UNCERTAINTY PROPAGATION USING POLYNOMIAL SURROGATES

Marc Balducci,[*] Juliana Feldhacker,[*] Jonathon Smith[†] and Brandon Jones[‡]

Approximations for the time-varying distribution of interplanetary orbit state uncertainty have traditionally relied on Gaussian assumptions or computationally expensive Monte Carlo (MC) methods. This generally leads to reduced accuracy of the propagated uncertainty in the first case, or an undesirable, and often intractable, number of orbit propagations in the latter. This paper considers the application of polynomial chaos (PC) for interplanetary orbit uncertainty propagation when there is one or more planetary or natural satellite flybys. The technique of compressive sampling is used in order to improve the tractability of the problem without sacrificing accuracy. The presented PC-based method of approximating the a posteriori probability density function requires no fundamental simplifying assumptions, reduces the computation time compared to MC, and produces a sensitivity analysis for the quantities of interest.

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ASTRODYNAMICS

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The following papers were not available for publication:

AAS 15-515	Paper Withdrawn
AAS 15-696	Paper Withdrawn
AAS 15-749	Paper Withdrawn

AAS 15-506

PERFORMANCE OF VARIABLE STEP NUMERICAL INTEGRATION ACROSS ECLIPSE BOUNDARY CROSSINGS FOR HAMR OBJECTS[*]

André Horstmann,[†] Vitali Braun[‡] and Heiner Klinkrad[‡]

The numerical integration process across eclipse boundaries will experience a rapid change in lighting condition, which may introduce large numerical errors due to the rapid changes of acceleration caused by solar radiation pressure. The acceleration of objects with high area-to-mass ratios (HAMR) is strongly affected by solar radiation pressure and may hold discontinuities. A typical behavior of variable-step multi-step integrators is the strong reduction or even a re-initialization of step size in the region of these eclipse crossing. By adapting the Lundberg correction algorithm for a fixed step integrator to a variable step integrator, it is able to cross the eclipse boundaries without the need of a very small stepsize or even an integrator restart. Consequently, the overall performance of the integrator used with the propagator NEPTUNE was increased by 1% to ≈ 2.7% for a 10-day MEO (a ≈ 20 000 km) orbit dependent on the number of eclipse boundary crossings.

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EQUILIBRIUM POINTS OF ELONGATED CELESTIAL BODIES AS THE PERTURBED ROTATING MASS DIPOLE

Xiangyuan Zeng,[*] Junfeng Li,[†] Hexi Baoyin[‡] and Kyle T. Alfriend[§]

The rotating mass dipole is adopted in this paper to approximate the gravitational field of the elongated celestial bodies. The equations of motion of the perturbed dipole model with oblateness of both primaries are derived to allow the existence of additional equilibrium points, including the points in the equatorial plane and in the plane *xoz*. Numerical simulations are performed to show the distribution of these equilibrium points along with zero-velocity curves around the dipole model. The effects of the oblateness of the primaries on the topological structure are also discussed based on the variation of zero-velocity curves.

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FORMATION FLYING CONSTANT LOW-THRUST CONTROL MODEL BASED ON RELATIVE ORBIT ELEMENTS

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

A new set of relative orbit elements (ROE) is used to establish a piecewise constant low-thrust control model for the satellites formation flying. An optimal objective function is defined in the control strategies of initialization, reconfiguration and configuration maintenance, which could be modified in terms of the formation requirements, such as the transfer error. The function extreme value has been solved by a nonlinear programming algorithm for the purpose of determining the propulsion time and scale. Furthermore, considering the impact of perturbations, a closed-loop feedback control law for configuration maintenance is derived. Numerical results indicate that the formation reconfiguration and configuration maintenance have been achieved through the low-thrust control method.

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AAS 15-511

SEMI-ANALYTICAL SPACECRAFT DYNAMICS AROUND PLANETARY MOONS

J. Cardoso dos Santos,[*] J. P. S. Carvalho,[†]
R. Vilhena de Moraes[‡] and A. F. B. A. Prado[§]

Several missions that propose to explore systems of planetary moons will require high-inclined orbits for gravity and surface mapping. In this context, this work aims to perform a search for these orbits considering gravitational disturbances on a spacecraft's orbit around different planetary moons. An analytical model for the third-body perturbation is developed, considering it in an eccentric-inclined orbit. The non-sphericity of some planetary moons is also considered. The dynamic of these orbits is explored by numerical simulations. The results satisfied the requirements for missions and complement the analytical studies found in the literature. Several orbits with inclinations in the order of 60° are found, which are below the critical inclination, but still gives a good coverage.

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AAS 15-512

EAST-WEST GEO SATELLITE STATION-KEEPING WITH DEGRADED THRUSTER RESPONSE

Yunhe Wu,[*] Stoian Borissov[†] and Daniele Mortari[‡]

The higher harmonic terms of Earth's gravitational potential slowly modify the nominal longitude of Geostationary Earth Orbit (GEO) satellites while the third-body presence (Moon and Sun) mainly affects its latitude. For this reason GEO satellites periodically need to perform station-keeping maneuvers, namely, East-West and North-South maneuvers to compensate for longitudinal and latitudinal variations, respectively. During the operational lifetime of GEO satellites, the thrusters' response when commanded to perform these maneuvers slowly departs from the original nominal impulsive behavior. This paper addresses the practical problem of how to perform reliable East-West station-keeping maneuvers when thruster response is degraded. The need for contingency intervention from ground based satellite operators is reduced by breaking apart the scheduled automatic station keeping maneuvers into smaller maneuvers. Orbital alignment and attitude are tracked on-board during and in between sub-maneuvers, and any off nominal variations are corrected for with subsequent maneuvers. These corrections are particularly important near the end of lifetime of GEO satellites, where thruster response farthest from nominal performance.

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AAS 15-514

GEOSYNCHRONOUS DEBRIS CONJUNCTION LEAD-TIME REQUIREMENTS FOR AUTONOMOUS LOW-THRUST DISPOSAL GUIDANCE

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

Autonomous, low-thrust guidance for active disposal of geosynchronous debris, subject to collision avoidance with the local debris population, is studied. A bisection method is employed to determine trajectory modifications to avoid a conjuncting debris object by a range of distances, assuming a range of collision lead times. A parametric study is performed, in which re-orbit thrust accelerations are varied from 10^{-6} to 10^{-3} m/s^2, to demonstrate how the continuous-thrust level impacts the required lead time to achieve a desired debris miss distance. The lowest thrust levels considered show that a 6-12 hour lead time is required to achieve a 1-10 km debris separation at the predicted collision time.

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AAS 15-516

TRAJECTORY AND STATE TRANSITION MATRIX ANALYTIC CONTINUATION ALGORITHMS

James D. Turner,[*] Abdullah Alnaqeb[†] and Ahmad Bani Younes[‡]

Series-based analytic continuation models have recently been shown to provide highly efficient and accurate trajectory propagation algorithms for celestial mechanics applications. A nonlinear change of variables is defined that enables one to generate recursive formulas for propagating vector-valued trajectories. Leibnitz product rule provides the core tool for generating arbitrary order time derivative models the position, velocity, and state transition matrix, which are propagated by summing Taylor series models. Cubic nonlinearities are handled by introducing sequential variable transformations. Solution accuracy and efficiency are controlled by two unknowns: (i) the time-step for the propagation, and (ii) the number of terms to be retained in the series approximation. Large time steps are enabled by introducing a variable step-size method that maintains sub-millimeter precision for orbit propagation. This work addresses the algorithmic extensions required for simultaneously generating the trajectory and state transition matrix solutions. Sparsity in the state transition matrix derivative calculations is exploited in the recursive formulation. The state transition group properties are used to assemble the segment solutions. A first order state transition matrix algorithm is formulated and tested. Numerical examples are presented that demonstrate the accuracy and effectiveness of the new series algorithm. Comparisons are provided for simulation run time and accuracy when comparing the algorithm with standard numerical integration methods.

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AAS 15-518

USING TAYLOR DIFFERENTIAL ALGEBRA IN MISSION ANALYSIS: BENEFITS AND DRAWBACKS

Vincent Morand[*], Jean Claude Berges, François Thevenot,
Emmanuel Bignon,[†] Pierre Mercier and Vincent Azzopardi

After having proved its potential in the field of particle beam physics, Taylor Differential Algebra (TDA) is being more and more used for space applications. As an example, the issues of Near Earth Objects encounters, orbital conjunctions and even long term orbit propagation can be analyzed using Taylor Differential Algebra. The field of mission analysis seems particularly suited for the use of TDA, since the uncertainty on inputs are generally high, parametrical studies are often required and computational efficiency is necessary. The paper details the TDA engine used in CNES (Centre National d'Etudes Spatiales, French space agency) and gives example of its applications for mission analysis.

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AAS 15-524

ORBIT DETERMINATION AND DIFFERENTIAL-DRAG CONTROL OF PLANET LABS CUBESAT CONSTELLATIONS

Cyrus Foster,* Henry Hallam† and James Mason‡

We present methodology and mission results from orbit determination of Planet Labs nanosatellites and differential-drag control of their relative motion. Orbit determination (OD) is required on Planet Labs satellites to accurately predict the positioning of satellites during downlink passes and we present a scalable OD solution for large fleets of small satellites utilizing two-way ranging. In the second part of this paper, we present mission results from relative motion differential-drag control of a constellation of satellites deployed in the same orbit.

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AAS 15-538

AN ANALYTIC PERTURBED LAMBERT ALGORITHM FOR SHORT AND LONG DURATIONS

Gim J. Der[*]

This paper presents an analytic perturbed multi-rev Lambert algorithm for any duration using a targeting technique with analytic perturbed state transition matrices. Since state transition matrices are commonly used in linear motion, it is intuitive not to use state transition matrices for long duration. When targeting by one step for the whole long duration is not possible, the given long duration can be divided into multiple small steps. As long as the perturbed state transition matrices can provide accurate targeting solutions with small time steps, an analytic perturbed multi-rev Lambert algorithm for long durations can be developed and used for rapid cataloging.

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AAS 15-540

HYBRID METHODS AROUND THE CRITICAL INCLINATION

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

In this work we apply a new approach, hybrid perturbation theory, to the problem of orbit propagation near the critical inclination. The critical inclination is a singular value which appears in both the direct and inverse transformation of the elimination of the perigee when the zonal harmonic J_2 of the geopotential is considered, thus preventing its application. We consider four different hybrid orbit propagators based on a closed-form second-order Brouwer-like analytical theory of the main problem, with different orders of approximation in J_2, complemented with an additive Holt-Winters method, and analyze their behavior near the critical inclination.

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ANALYTICAL APPROXIMATIONS TO THE GENERALIZATION OF THE KEPLER EQUATION

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

The generalized Kepler equation is a transcendental non-linear equation which appears in the zonal problem of the artificial satellite theory when the Krylov-Bogoliubov-Mitropolsky method is employed. In this work, the Lie-Deprit method is used to apply Lagrange's inversion theorem in order to solve the generalized Kepler equation. For small eccentricities, the analytical approximate solution yields similarly accurate results to numerical methods. For the rest of eccentricities, we discuss the applicability of this approximation as an initial guess in the numerical method used to solve the generalized Kepler equation.

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AAS 15-544

AN INTRUSIVE APPROACH TO UNCERTAINTY PROPAGATION IN ORBITAL MECHANICS BASED ON TCHEBYCHEFF POLYNOMIAL ALGEBRA

Annalisa Riccardi,[*] Chiara Tardioli[†] and Massimiliano Vasile[‡]

The paper presents an intrusive approach to propagate uncertainty in orbital mechanics. The approach is based on an expansion of the uncertain quantities in Tchebycheff series and a propagation through the dynamics using a generalised polynomial algebra. Tchebycheff series expansions offer a fast uniform convergence with relaxed continuity and smoothness requirements. The paper details the proposed approach and illustrates its applicability through a set of test cases considering both parameter and model uncertainties. This novel intrusive technique is then compared against its non-intrusive counterpart in terms of approximation accuracy and computational complexity.

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AAS 15-572

MODE ANALYSIS FOR LONG-TERM BEHAVIOR IN A RESONANT EARTH–MOON TRAJECTORY

Cody Short,[*] Kathleen Howell,[†] Amanda Haapala[‡] and Donald Dichmann[§]

Trajectory design in chaotic regimes allows for the exploitation of system dynamics to achieve certain behaviors. For the Transiting Exoplanet Survey Satellite (TESS) mission, the selected science orbit represents a stable option well-suited to meet the mission objectives. Extended, long-term analysis of particular solutions nearby in the phase space reveals transitions into desirable terminal modes induced by natural dynamics. This investigation explores the trajectory behavior and borrows from flow-based analysis strategies to characterize modes of the motion. The goal is to identify mechanisms that drive the spacecraft into a particular mode and supply conditions necessary for such transitions.

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AAS 15-603

REVIEW OF MISSION DESIGN AND NAVIGATION FOR THE VAN ALLEN PROBES PRIMARY MISSION

Justin A. Atchison[*] and Fazle E. Siddique[*]

NASA's two Van Allen Probes spacecraft completed their primary mission on November 1, 2014 following two years of successful operation. This paper reviews their operations with respect to mission design and navigation. In terms of mission design, all requirements were met with no trajectory correction maneuvers. The observed orbit evolution matches predictions to a high accuracy. Three unplanned collision avoidance maneuvers were performed. Of the potential collisions, roughly 70% of the objects were associated with debris. In terms of navigation, historical overlap comparisons indicate that the 7 day prediction accuracy is better than 9 km for 95% of the samples, and the mission's 22 km accuracy requirement is always satisfied. Compared to the ensemble of overlap errors, the computed prediction covariance is inaccurately high. This error is likely caused by the method by which the software accommodated an unmodeled variation in the Doppler data associated with each spacecraft's antenna phase center not being located along the spin-axis.

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AAS 15-604

ORBIT AND ATTITUDE STABILITY CRITERIA OF SOLAR SAIL ON THE DISPLACED ORBIT

Junquan Li,[*] Mark A. Post[†] and George Vukovich[‡]

The polar regions of the Earth are of particular interest to spacecraft missions in terms of monitoring, provision of communications and resource exploration, and biasing the coverage provided in northern latitudes also has commercial advantages. This paper studies orbit and attitude stability criteria for a solar sail spacecraft that could serve this region and possible strategies for acquisition using the limited resources to miniaturized spacecraft without a propulsion system. A coupled orbit and attitude stability analysis for a spacecraft using solar radiation pressure for displaced orbits provides results based on stability and control-lability criteria.

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AAS 15-610

SATELLITE FORMATION-KEEPING ABOUT LIBRATION POINTS IN THE PRESENCE OF SYSTEM UNCERTAINTIES

Mai Bando,[*] Hamidreza Nemati[†] and Shinji Hokamoto[‡]

This paper studies a control law to stabilize the orbital motion in the vicinity of an unstable equilibrium points and periodic orbits in the circular-restricted three-body problem. Utilizing the eigenstructure of the system, the fuel efficient formation flying controller via linear quadratic regulator (LQR) is developed. Then the chattering attenuation sliding mode controller (CASMC) is designed and analyzed for the in-plane motion of the circular circular-restricted three-body problem. Simulation studies are conducted for the Sun-Earth L_2 point and a halo orbit around it. The total velocity change required to reach the halo orbit as well as to maintain the halo orbit is calculated. Simulation results show that the chattering attenuation sliding mode controller has good performance and robustness in the presence of unmodeled nonlinearity along the halo orbit with relatively small fuel consumption.

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AAS 15-615

ISOLATING BLOCKS AS COMPUTATIONAL TOOLS IN THE CIRCULAR RESTRICTED THREE-BODY PROBLEM[*]

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

Isolating blocks may be used as computational tools to search for the invariant manifolds of orbits and hyperbolic invariant sets associated with libration points while also giving additional insight into the dynamics of the flow in these regions. We use isolating blocks to investigate the dynamics of objects entering the Earth-Moon system in the circular restricted three-body problem with energies close to the energy of the L_2 libration point. Specifically, the stable and unstable manifolds of Lyapunov orbits and the hyperbolic invariant set around the libration points are obtained by numerically computing the way orbits exit from an isolating block in combination with a bisection method. Invariant spheres of solutions in the spatial problem may then be located using the resulting manifolds.

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END OF LIFE DISPOSAL FOR THREE LIBRATION POINT MISSIONS THROUGH MANIPULATION OF THE JACOBI CONSTANT AND ZERO VELOCITY CURVES

Jeremy D. Petersen[*] **and Jonathan M. Brown**[†]

The aim of this investigation is to determine the feasibility of mission disposal by inserting the spacecraft into a heliocentric orbit along the unstable manifold and then manipulating the Jacobi constant to prevent the spacecraft from returning to the Earth-Moon system. This investigation focuses around L1 orbits representative of ACE, WIND, and SOHO. It will model the impulsive ΔV necessary to close the zero velocity curves after escape through the L1 gateway in the circular restricted three body model and also include full ephemeris force models and higher fidelity finite maneuver models for the three spacecraft.

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AAS 15-626

DESIGN AND APPLICATIONS OF SOLAR SAIL PERIODIC ORBITS IN THE NON-AUTONOMOUS EARTH-MOON SYSTEM

Jeannette Heiligers,[*] Malcolm Macdonald[†] and Jeffrey S. Parker[‡]

Solar sailing has great potential for a range of high-energy and long duration missions in the Sun-Earth system. This paper extends this potential to the non-autonomous Earth-Moon system through the use of a differential correction scheme, and by selecting suitable in-plane and out-of-plane sail steering laws to develop new families of solar sail libration point orbits that are periodic with the Sun's motion around the Earth-Moon system. New orbits include those that bifurcate from the natural Lyapunov, halo and eight-shaped orbit families at the first and second Lagrange points. The potential of these orbits is demonstrated by considering the performance of a subset of orbits for high-latitude Earth observations, lunar far-side communications, and lunar South Pole coverage.

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AAS 15-632

SEP MISSION DESIGN SPACE FOR MARS ORBITERS

Ryan C. Woolley[*] and Austin K. Nicholas[†]

The advancement of solar-electric propulsion (SEP) technologies and larger, light-weight solar arrays offer a tremendous advantage to Mars orbiters in terms of both mass and timeline flexibility. These advantages are multiplied for round-trip orbiters (e.g. potential Mars sample return) where a large total ΔV would be required. In this paper we investigate the mission design characteristics of mission concepts utilizing various combinations and types of SEP thrusters, solar arrays, launch vehicles, launch dates, arrival dates, etc. SEP allows for > 50% more mass delivered and launch periods of months to years. We also present the SEP analog to the ballistic Porkchop plot – the "Bacon" plot.

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AAS 15-637

DYNAMICAL EVOLUTION ABOUT ASTEROIDS WITH HIGH FIDELITY GRAVITY FIELD AND PERTURBATIONS MODELING

Andrea Colagrossi,[*] Fabio Ferrari,[†] Michèle Lavagna[‡] and Kathleen Howell[§]

The paper presents different strategies to model the gravitational field in the vicinity of irregular celestial bodies, such as asteroids and comets. The gravitational attraction of these irregular objects has been modeled, through accurate shape discretization, with a constant density polyhedron or an ensemble of point masses. In the latter case, an optimization algorithm to distribute the mass elements within the volume of the body has been developed. All the different modeling techniques are compared in order to highlight their advantages and drawbacks. In addition, an extensive analysis of the results is performed with the purpose to find the model that has an optimal balance between level of accuracy and required computational effort.

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AAS 15-657

THE EUROPA MISSION: MULTIPLE EUROPA FLYBY TRAJECTORY DESIGN TRADES AND CHALLENGES

Try Lam,[*] Juan J. Arrieta-Camacho[*] and Brent B. Buffington[*]

With potential sources of water, energy and other chemicals essential for life, Europa is a top candidate for finding current life in our Solar System outside of Earth. This paper describes the current trajectory design concept for a multiple Europa flyby mission and discusses several trajectory design challenges. The candidate reference trajectory utilizes multiple Europa flybys while around Jupiter to enable near global coverage of Europa while balancing science requirements, radiation dose, propellant usage, and flight time. Trajectory design trades and robustness are also discussed.

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AAS 15-661

COMPACT SOLUTION OF CIRCULAR ORBIT RELATIVE MOTION IN CURVILINEAR COORDINATES

Claudio Bombardelli,[*] Juan Luis Gonzalo[†] and Javier Roa[†]

A compact approximate solution of the highly non-linear relative motion in curvilinear coordinates is provided under the assumption of circular orbit for the chief spacecraft and moderately small inclination and eccentricity for the follower. The rather compact three-dimensional solution, which employs time as independent variable, is obtained by algebraic manipulation of the individual Keplerian motions in curvilinear coordinates and Taylor expansion for small eccentricity of the follower orbit. Numerical test cases are conducted to show that the approximate solution can be effectively employed to extend the classical linear Clohessy-Wiltshire solution to include non-linear relative motion without significant loss of accuracy up to a limit of 0.4-0.5 in eccentricity and a few degrees in inclination.

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ANALYTIC POWER SERIES SOLUTIONS FOR TWO-BODY AND J_2–J_6 TRAJECTORIES AND STATE TRANSITION MODELS

Kevin Hernandez,[*] Julie L. Read,[*] Tarek A. Elgohary,[†]
James D. Turner[‡] and John L. Junkins[§]

Recent work has shown that two-body motion can be analytically modeled using analytic continuation models, which utilize kinematic transformation scalar variables that can be differentiated to an arbitrary order using the well-known Leibniz product rule. This method allows for large integration step sizes while still maintaining high accuracy. With these arbitrary order time derivatives available, an analytical Taylor series based solution may be applied to propagate the position and velocity vectors for the nonlinear two-body problem. This foundational method has been extended to demonstrate a highly effective variable step-size control for the analytic continuation Taylor series model. The current work builds on these earlier results by extending the analytic power series approach to trajectory calculations for two-body and J_2–J_6 gravity perturbation terms.

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AAS 15-666

SEARCHING FOR MORE STABLE PERTURBED ORBITS AROUND THE EARTH

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

The goal of the present paper is to search for orbits around the Earth that are more stable, in the sense of presenting minimum variations with respect to a Keplerian initial orbit. This variation will be measured by the integral of the differences of the radius vector of the real perturbed orbit and the equivalent vector of the Keplerian orbit that starts at the same point. The search for stable orbits is carried out by making maps of the integral of the magnitude of the disturbing forces. Particularly, the effects of the semi-major axis and the eccentricity of the orbit in those mappings are studied. The disturbing forces considered here are the solar radiation pressure, the Luni-Solar perturbation and the zonal harmonics J_2 to J_4. The results of these integrals are the velocity increment that the perturbation delivers to the satellite. The possibility of using a solar sail to reduce the effects of the other perturbations acting on the satellite is considered using this approach and it shows to be a useful idea.

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AAS 15-678

APPLICATIONS OF RELATIVE SATELLITE MOTION MODELING USING CURVILINEAR COORDINATE FRAMES

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

This paper compares various satellite relative motion solutions previously derived via nonlinear transformations from a curvilinear coordinate frame to a Cartesian frame. The solutions can be compared by creating difference contour plots that show the difference of the maximum position error between two solutions. These contours show regions where one solution has more accuracy over another solution according to the varying parameters used to create the difference contours. A relative maneuver targeting algorithm based on Lambert's problem is developed using a cylindrical coordinate frame and compared with known Cartesian and second order relative motion maneuver targeting algorithms. The utility of formulating the relative maneuver targeting problem is shown and contour plots are created that show the maneuvering miss distance calculated by varying relevant relative motion parameters.

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AAS 15-679

RELATIVE SATELLITE MOTION OPTIMAL CONTROL USING CONVEX OPTIMIZATION

Alex Perez,[*] Jacob Gunther[†] and David K. Geller[‡]

Convex optimization theory is applied to relative satellite motion to determine the optimal control profile for satellite rendezvous scenarios. The relative satellite rendezvous problem is shown to be convex when using the Hill-Clohessy Wiltshire linearized ordinary differential equations as the governing dynamics. Several inequality constraints are imposed on the convex problem in order to simulate keep-out zones, rendezvous corridors and navigation line-of-sight constraints. Several cases of satellite rendezvous are presented with different objective functions to briefly show the utility and robustness of the convex optimization algorithm applied to relative satellite rendezvous.

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AAS 15-684

ANALYTICAL PERTURBATION THEORY FOR DISSIPATIVE FORCES IN TWO-POINT BOUNDARY VALUE PROBLEMS

Oier Peñagaricano Muñoa[*] and Daniel J. Scheeres[†]

An analytical perturbation technique for solving two-point boundary value problems is presented. The technique builds on previous work done in the perturbation theory for Hamilton's principal function and used to analytically solve for the velocities in the perturbed targeting problem. The method presented extends to dissipative forces such as aerodynamic drag, and only requires the nominal two-body solution. Applications of the theory are found primarily in the fields of orbital mechanics and optimal control. The technique is validated through numerical simulations.

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AAS 15-689

SPACE PARTITIONING STRUCTURES FOR EFFICIENT STABILITY MAP GENERATION

Navid Nakhjiri[*]

Stable orbits are known candidates for designing long-term science missions in perturbed dynamical environments. Finding stable regions within a domain of phase space often requires a tedious investigation. Traditionally, a uniform sampling of initial states from phase-space is needed to generate a stability map, which reveals stable regions. However, an adaptive non-uniform grid can significantly reduce the computation efforts. In this paper, a series of space partitioning structures have been explored for the purpose of adaptively generating a non-uniform grid that is dense near the boundaries of the stable regions and sparse elsewhere.

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AAS 15-691

CONVEX CONSTRAINTS ON STABILITY FOR IMPULSIVE TRANSFER OPTIMIZATION

Eric Trumbauer[*] and Navid Nakhjiri[†]

Stable transfers have been proposed as a transfer strategy to guarantee mission recovery under the risk of maneuver or modeling errors. These transfers consist of a sequence of impulses such that the trajectory stays within the stable region of the dynamics at all times. As convex optimization becomes increasingly popular for both autonomous and ground based design, it is possible to include stability constraints directly into the problem formulation. This paper explores the derivation and application of second-order cone stability constraints and analyzes their effect on established convergence properties of these optimization methods.

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AAS 15-713

EXPANSION OF DENSITY MODEL CORRECTIONS DERIVED FROM ORBIT DATA TO THE ANDE SATELLITE SERIES

Travis Lechtenberg,[*] Craig McLaughlin[†] and Harold Flanagan[‡]

Current techniques to estimate corrections to atmospheric density are expanded to the ANDE satellite series. These are tracked using satellite laser ranging, while having firmly established drag characteristics. These corrections yield estimated density corrections which in turn lead to better drag estimates, improved orbit determination and prediction, as well as an enhanced understanding of density variations in the thermosphere and exosphere. This examination will give a better idea of obtainable improvements in atmospheric density. Consideration will also be given to the effects of varying levels of geomagnetic and solar activity.

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AAS 15-731

HIGH ORDER TRANSFER MAP METHOD AND GENERAL PERTURBATION TECHNIQUES APPLIED TO PERTURBED KEPLERIAN MOTION

Roberto Armellin,[*] Alexander Wittig[†] and Juan Felix San Juan[‡]

The present international concern in space situational awareness has produced a renewed interest in efficient methods for propagation of catalogs of data. Recently, a new technique called high-order transfer map (HOTM) method has been proposed to deal with the problem of perturbed Keplerian dynamics. This technique is based on the numerical integration of a single orbital revolution in differential algebra arithmetic, yielding an analytical high order approximation of the true transfer map. It is then followed by its repeated analytical evaluation to advance the orbital propagation by several orbital periods. The main focus of this work is to extend the HOTM approach in the case of highly non-autonomous perturbations and to compare it with analytical and semi-analytical propagators based on Lie transforms. Objects in Low Earth Orbit, Geosynchronous Transfer Orbit, and a Molniya orbit are used as test cases.

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AAS 15-734

DEALING WITH UNCERTAINTIES IN INITIAL ORBIT DETERMINATION

Roberto Armellin,[*] Pierluigi Di Lizia[†] and Renato Zanetti[‡]

A method to deal with uncertainties in initial orbit determination (IOD) is presented. This is based on the use of Taylor differential algebra (DA) to nonlinearly map the observation uncertainties from the observation space to the state space. When a minimum set of observations is available, DA is used to expand the solution of the IOD problem in Taylor series with respect to measurement errors. When more observations are available, high order inversion tools are exploited to obtain full state pseudo-observations at a common epoch. The mean and covariance of these pseudo-observations are nonlinearly computed by evaluating the expectation of high order Taylor polynomials. Finally, a linear scheme is employed to update the current knowledge of the orbit. Angles-only observations are considered and simplified Keplerian dynamics adopted to ease the explanation. Three test cases of orbit determination of artificial satellites in different orbital regimes are presented to discuss the feature and performances of the proposed methodology.

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INVESTIGATING THE EVOLUTION OF PRACTICAL DISTANT RETROGRADE ORBITS UP TO 30,000 YEARS

Collin Bezrouk[*] **and Jeffrey S. Parker**[†]

This work studies the evolution of several Distant Retrograde Orbits (DROs) in the Earth-Moon system with varying sizes and inclinations over tens of thousands of years. This analysis is relevant for missions requiring a completely handsoff, long duration quarantine orbit, such as a Mars Sample Return mission or the Asteroid Redirect Mission. Four DROs, selected from four stable size regions, are propagated with quadruple precision arithmetic and a high fidelity dynamics model for 30,000 years. The evolution of the orbit size, shape, orientation, period, out-of-plane amplitude, and Jacobi constant are tracked. It was found that small DROs, with an x-amplitude of approximately 45,000 km or less decay in size and period largely due to the Moon's solid tides. Larger DROs (62,000 km and up) are more influenced by the gravity of bodies external to the Earth-Moon system, and remain bound to the Moon for significantly less time.

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AAS 15-761

GRASP ALGORITHM FOR MULTI-RENDEZVOUS MISSION PLANNING WITH OPTIMIZED TRIP TIMES

Atri Dutta[*]

The paper considers the Greedy Random Adaptive Search Procedure to optimize a sequence of rendezvous maneuvers by a spacecraft with multiple targets. The algorithm consists of two phases: the first phase constructs feasible solutions of the problem, and the second phase performs local search about the constructed solution. In this paper, we focus on the problem of optimization of individual trip times to each target during the mission, where each individual transfer orbit is considered to be multi-revolution solution to the Lambert's problem. We demonstrate our methodology using numerical examples for planar targets in a circular orbit.

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AAS 15-770

SEARCHING FOR PERIODIC AND QUASI-PERIODIC ORBITS OF SPACECRAFTS ON THE HAUMEA SYSTEM

Diogo M. Sanchez,[*] Antonio F. B. A. Prado[†] and Tadashi Yokoyama[‡]

In this work, we explore regions around the two moons of the dwarf planet Haumea, Namaka and Hi'iaka, in order to provide options for a mission to this system. Using a model with the perturbation of the Sun, Namaka and Hi'iaka, and the gravitational potential of Haumea up to degree and order four, we map the survival time of a spacecraft in a wide range of initials semi-major axis and inclination. Then, we found apparently stable orbits in the vicinity of Namaka and Hi'iaka. Finally, using the restricted three body problem, Poincaré sections were made in order to find periodic and quasi-periodic orbits around these two moons.

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AAS 15-798

LONG TERM EVOLUTION OF THE ECCENTRICITY IN THE MEO REGION: SEMI-ANALYTICAL AND ANALYTICAL APPROACH

Florent Deleflie,[*] J. Daquin,[†] E. M. Alessi[‡] and A. Rossi[‡]

We study the long term evolution of the mean eccentricity of trajectories within the MEO region, and in particular at altitudes corresponding to Galileo nominal or disposal cases, following a semi-analytical and an analytical approach. The model accounts for all the significant perturbations acting on the trajectories: zonal and tesseral parameters of the Earth's gravity field, luni-solar attraction, atmospheric drag when relevant; we study the time evolution of the two components of the eccentricity vector, depending on the choice of the initial conditions: long period variations, that could even been seen as secular effects over some periods, are interpreted in terms of the influence of the luni-solar attraction. Maps of maximal eccentricity reached over less than 2 centuries are performed with the STELA s/w, and the role played by the $\Omega + 2\omega$ resonance is underlined.

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AAS 15-799

OPTIMAL FORMATION DESIGN OF A MINIATURIZED DISTRIBUTED OCCULTER/TELESCOPE IN EARTH ORBIT

Adam W. Koenig,[*] Simone D'Amico,[†] Bruce Macintosh[‡] and Charles J. Titus[§]

This paper presents a novel formation design methodology for a miniaturized distributed occulter/telescope (mDOT) in earth orbit. In contrast to large-scale missions such as the New Worlds Observer or Exo-S (NASA), mDOT makes use of micro- and nano-satellites inertially aligned in earth orbit to reduce mission costs by orders of magnitude. Due to the small telescope aperture, this concept requires greater instrument integration time (or observation duration) in an environment with larger differential accelerations. As a consequence, a formulation of delta-v optimal absolute and relative orbits represents a mission enabler. The key contributions of this paper stem from the fundamental idea that the delta-v cost of observations can be optimized by allowing the formation to freely drift along the observation axis. First, this work presents an analytical expression of the delta-v cost of a pareto-optimal family of finite forced motion control maneuvers. Second, a method of selecting the initial argument of perigee and right ascension of the ascending node is presented that minimizes the deviation of the formation from its optimal configuration due to secular J_2 effects. Furthermore, it is demonstrated through high-fidelity numerical simulations that the delta-v optimal configuration with respect to forced motion control is also globally delta-v optimal. Finally, these simulations are used to show that the total delta-v cost for a mission consisting of multiple observations of a single target is well within the capacity of current small satellite propulsion systems.

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SEASONAL VARIATIONS OF THE JAMES WEBB SPACE TELESCOPE ORBITAL DYNAMICS

Jonathan Brown,[*] Jeremy Petersen,[†] Benjamin Villac[‡] and Wayne Yu[§]

While spacecraft orbital variations due to the Earth's tilt and orbital eccentricity are well-known phenomena, the implications for the James Webb Space Telescope present unique features. We investigate the variability of the observatory trajectory characteristics, and present an explanation of some of these effects using invariant manifold theory and local approximation of the dynamics in terms of the restricted three-body problem.

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AAS 15-803

ANALYTICAL CONVERSION OF MEAN ORBITAL ELEMENTS INTO OSCULATING ELEMENTS FOR FROZEN ORBIT ABOUT ASTEROIDS

Inkwan Park[*] and Daniel J. Scheeres[†]

The analytical conversion algorithm of mean orbital elements' space is discussed in this study. In particular, we apply the algorithm to map a frozen or quasi-frozen orbit defined in mean orbital elements' space about asteroids into osculating elements' space. We expect that frozen orbits become more applicable, such as introducing control law, through the analytical conversion. For this study, a perturbation theory is exploited in order to derive both an averaged (normalized) equation and a generating function. The suggested algorithm is applied to two different perturbed Keplerian motions about asteroid 101955 Bennu.

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ATTITUDE DYNAMICS AND CONTROL

Session Chairs:

Kyle DeMars, Missouri University of Science and Technology
Maruthi Akella, The University of Texas at Austin
Sergei Tanygin, Analytical Graphics, Inc.
Mark Karpenko, Naval Postgraduate School
Robert Melton, Pennsylvania State University
David C. Hyland, Texas A&M University

The following papers were not available for publication:

AAS 15-672 Paper Withdrawn
AAS 15-680 Paper Withdrawn
AAS 15-683 Paper Withdrawn

AAS 15-502

UNDAMPED PASSIVE ATTITUDE STABILIZATION AND ORBIT MANAGEMENT OF A 3U CUBESAT WITH DRAG SAILS

Siddharth S. Kedare[*] and Steve Ulrich[†]

This paper evaluates the effectiveness of drag sails on maintaining a ram-facing orientation for a 3U CubeSat in Equatorial Low Earth Orbit. The influence of varying the drag sail area and inertia tensor on the aerostabilization characteristics and orbit of the spacecraft is examined through computational modeling of the spacecraft dynamics in Matlab-Simulink. The study also investigates the ability of a commercially available attitude control system to slew the spacecraft into a low-drag orientation to extend orbital lifetime. The results indicate that undamped aerostabilization of a 3U CubeSat is feasible, and provides acceptable conditions for limited scientific observation. In addition, the simulation results demonstrate that the spacecraft is capable of entering and maintaining a low-drag orientation for five days without reaction wheel saturation.

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AAS 15-504

AN EPITAXIAL DEVICE FOR MOMENTUM EXCHANGE WITH THE VACUUM STATE

David C. Hyland[*]

This paper re-examines the dynamic Casimir effect as a possible mechanism for propulsion. Previous investigations assumed mechanical motion of a mirror to generate thrust. In this case, because of the finite strength of materials and the high frequencies necessary, the amplitudes of motion must be restricted to the nanometer range. Here, we propose an epitaxial stack of transparent semiconductor laminae. Voltage is rapidly switched to successive lamina, creating continuous, large amplitude motion of a reflective surface without mechanical contrivances. The paper provides correct relativistic results for large amplitude motion. With meter-level magnitudes, propulsive forces are raised to significant levels.

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AAS 15-509

INFLUENCE ANALYSIS OF THE IMPACTS AND FRICTIONS OF THE JOINTS OF THE VIBRATION ISOLATION PLATFORM FOR CONTROL MOMENT GYROSCOPE

Zixi Guo,[*] Jingrui Zhang, Yao Zhang, Liang Tang[†] and Xin Guan

This paper discusses the dynamic characteristics of the impacts and corresponding frictions generated by the clearances of joints of vibration isolation platforms for control moment gyroscopes (CMGs) on spacecraft. A contact force model is applied using a nonlinear contact force model, and the frictions in the joints are considered in the dynamic analysis. First, the dynamic characteristics of a single isolation strut with spherical joints were studied, and joints with different initial clearance sizes were separately analyzed. Then, dynamic models of the vibration isolation platform for a CMG cluster with both perfect joints and joints with clearances were established. During the numeral simulation, joints with different elastic moduli were used to study the nonlinear characteristics.

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AAS 15-525

GROUND INTENSITY DISTRIBUTION OF THE POWER STAR^{TM}

David C. Hyland[*]

Power Star^{TM} is a space solar power satellite in the form of a spherical balloon deployed at geostationary altitude. The balloon is composed of a thin membrane upon which are printed solar cells and microwave patch antennas. Using retro-directive phased array technology, the latter devices beam microwave power to ground-based rectennas, designated by microwave beacons. Assuming that solar cells and antennas cannot occupy the same areas, randomized placement of the antennas is needed to avoid grating lobes. This paper precisely calculates the ground-plane power density distribution produced by the satellite with random antenna placement in response to a point-source beacon.

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AAS 15-542

ON-ORBIT EXPERIENCE OF FLYING TWO-WHEEL CONTROLLED SATELLITES

Johannes Hacker,[*] Peter C. Lai[†] and Jiongyu Ying[‡]

Following several reaction wheel on-orbit anomalies and ensuing lifetime extension of the Globalstar 2nd generation fleet, a hybrid control algorithm using two wheels and magnetic torque bars was developed and implemented in the satellites in low Earth orbit. Since the control torque by magnetics is much smaller than that by reaction wheel and its strength varies with satellite position and attitude on the orbit, satellite operations engineers must take special care during station keeping, yaw slew, etc. This paper will present some on-orbit data and les-sons learned associated with this new hybrid control algorithm.

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AAS 15-549

FRACTIONAL ORDER CAYLEY TRANSFORMS FOR DUAL QUATERNIONS BASED POSE REPRESENTATION

Daniel Condurache[*] and Adrian Burlacu[†]

This main goal of this research is the development of a new pose parametrization technique based on fractional order Cayley transforms. Our study is based on the properties of maps that link dual vectors with unitary dual quaternions. For the first time a complete parametrization framework is constructed, completely embeds multiple of the reported attitude parameterization Cayley maps and extends them towards pose parameterization. The novelty of our methods over existing solutions is discussed and the main advantages are revealed.

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SPACECRAFT ATTITUDE TRACKING CONTROL BASED ON DIFFERENTIAL GEOMETRY THEORY

Jianjun Luo,[*] Zeyang Yin,[†] Baichun Gong[‡] and Jianping Yuan[§]

This paper presents a novel methodology to solve the attitude tracking control problem of a spacecraft system with external disturbances and parameters uncertainties. The new nonlinear control approach is based on differential geometry theory and Active Disturbances Rejection Control (ADRC). For spacecraft attitude tracking error equations, exact linearization for the nonlinear system is realized through output feedback based on Lie derivation. The linearized system is controlled by means of ADRC, which is effective in external disturbances rejection. ADRC in linearized system is then mapped back to original system to obtain the spacecraft attitude tracking control law based on differential geometry theory. In order to overcome the negative effect on the control system caused by parameter uncertainties, this approach is developed using Improved Particle Swarm Optimization (IPSO) algorithm to realize on-line parameters identification. Traditional PSO algorithm is improved using reliability factor to minimum the effect of external disturbances on parameters identification. Numerical simulations are finally given to demonstrate the performance of the proposed methodology.

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AAS 15-573

ATTITUDE CONTROL OF A MODULAR NPU-PHONESAT BASED ON SHAPE ACTUATION

Qiao Qiao,[*] Jianping Yuan,[†] Xin Ning[‡] and Baichun Gong[§]

This paper investigates the attitude control of a modular NPU-PhoneSat based on shape actuation. The PhoneSat is composed of multiple blocks connected by active joints. Much like a falling cat can reorient itself in mid-air, this modular PhoneSat could reorient itself without changes in net angular momentum by altering the shape and instantaneous mass distribution during attitude maneuvers. Given size and cost constraints, the number of actuators should be limited. Thus, this paper focuses on the under-actuated case. Optimal attitude control method to steer the PhoneSat to the desired posture is proposed, with the objective to minimize the input energy. The inequality constraints are established based on the capacity of the actuator. Particle Swarm Optimization algorithm is employed to search the optimal control input to achieve the reorientation while satisfying the imposed constraints. The input torques is parametrized by the spline to guarantee that initial and final values of control input are zero. Simulation results of zero-angular-momentum reorientations of the PhoneSat are presented and confirm the effectiveness of the proposed method.

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AAS 15-596

FIXED-TIME CONTROL DESIGN FOR SPACECRAFT ATTITUDE STABILIZATION

Li Yuan,[*] Boyan Jiang,[†] Chuanjiang Li,[‡] Guangfu Ma[§] and Yanning Guo[**]

Fixed-time controller features an upper bound of settling time, which does not depend on initial states of control system. In view of that nearly all the existing fixed-time control methods are based on the terminal sliding mode, a new fixed-time control law is developed by using a special Lyapunov function with a power integrator form for the spacecraft attitude stabilization in the presence of external disturbance. The bounded convergence time is given through a strictly theoretical deduction. Numerical simulations are performed to illustrate the effectiveness of the proposed fixed-time control scheme in the spacecraft attitude control system.

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DECREASING THE FREQUENCY OF LUNAR RECONNAISSANCE ORBITER MOMENTUM UNLOADS USING SOLAR ARRAY POINTING AND ATTITUDE MANEUVERS TO CONTROL ANGULAR MOMENTUM

Russell DeHart[*] and Milton Phenneger[†]

The Lunar Reconnaissance Orbiter (LRO) is a three-axis stabilized spacecraft that uses hydrazine thrusters during reaction wheel assembly (RWA) momentum unloads. Some instrument activities and solar array configurations have been observed to be constructive or destructive to trends in spacecraft angular momentum. This analysis explores these as alternate methods to unload RWA angular momentum. On average, system body coordinate system (BCS) Y angular momentum, H_Y, either increases by approximately 3.9 Nms/day or decreases by approximately 1.1 Nms/day, depending on spacecraft configuration. On average, H_X and H_Z each increase by 2.3 Nms/day. Systems engineers with the Space Science Mission Operations project at NASA Goddard Space Flight Center are developing the LRO Angular Momentum Simulation (LAMS), which predicts the RWA angular momentum over a user-defined period of time. For parked so-lar array configurations, LAMS data suggest offsets of +2.4° and +5.0° to the inner gimbal would nullify growth in RWA H_Y for the (–90°, +45°) and (–90°, +15°) solar array (inner, outer) configurations, respectively. Larger offsets are necessary when using the outer gimbal to control RWA H_{XZ}. For the (–90°, +45°) and (–90°, +15°) configurations, offsets of +22° and +60°, respectively, were necessary. Operational constraints limit the application of the full offsets, though, especially for the (–90°, +45°) configuration. Removing overall angular momentum trends in the vicinity of attitude maneuvers allows the measurement of maneuver-induced changes in system angular momentum. This trending analysis identifies –90° CRaTER instrument calibration roll and ±45° LROC exospheric measurement pitch slews as candidates for angular momentum control. CRaTER roll maneuvers increased system BCS H_Y by up to 2.8 Nms. The magnitude of changes in system in-plane angular momentum was limited to less than 1 Nms. Each ±45° LROC exosphere measurement pitch slew changes the system BCS H_Y by approximately 0.5 Nms, while leaving H_{XZ} essentially unchanged. Once the LAMS has been fully verified, it can be used to explore notional scenarios, instead of relying on trending analysis which is limited to measuring the effects of activities that have actually been performed. [View Full Paper]

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LYAPUNOV BASED ATTITUDE CONSTRAINED CONTROL OF A SPACECRAFT

Monimoy Bujarbaruah* **and Srikant Sukumar†**

The article deals with the problem of imposing attitude constraints during trajectory tracking for a spacecraft. A Lyapunov function based approach is utilized to develop a novel nonlinear backstepping controller for implementation of the imposed attitude constraints, while guaranteeing reference attitude tracking. The result combines a static optimization and Lyapunov function based approach to ensure that initial conditions starting within the attitude constraint boundary stay within the same for all time.

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AAS 15-605

ANALYSIS OF THE GAUSS-BINGHAM DISTRIBUTION FOR ATTITUDE UNCERTAINTY PROPAGATION

Jacob E. Darling[*] **and Kyle J. DeMars**[†]

Attitude uncertainty quantification typically requires a small angle assumption, and thus an inherent small uncertainty assumption, to be made. This small angle assumption can be eliminated by employing the Bingham distribution to represent the attitude uncertainty in the attitude quaternion directly. Moreover, an extension to the Bingham distribution, termed the Gauss-Bingham distribution, can be used to represent correlated attitude quaternion and angular velocity uncertainty to enable attitude uncertainty propagation. In order to evaluate the potential accuracy gain using the Gauss-Bingham distribution for attitude uncertainty quantification, the Gauss-Bingham distribution method for attitude uncertainty propagation is compared to the propagation step of the multiplicative extended Kalman filter, which requires a small angle assumption to be made. The attitude uncertainty quantified by each method is discretely sampled and mapped to a common attitude parameterization in order to make accurate comparisons between each method.

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AAS 15-614

APPLICATION OF THE REGULARIZED PARTICLE FILTER FOR ATTITUDE DETERMINATION USING REAL MEASUREMENTS OF CBERS-2 SATELLITE

William R. Silva,* **Hélio K. Kuga**† **and Maria C. Zanardi**‡

In this work, the attitude determination and the gyros drift estimation using the Regularized Particle Filter (RPF) with Roughening for nonlinear systems will be described. The application uses the real measurement data for orbit and attitude of the CBERS-2 (China Brazil Earth Resources Satellite) that are compared with the simulated measurements, with low and high sampling rate, emulating the real conditions of CBERS-2 satellite. The simulated measurements were provided by the package PROPAT, a Satellite Attitude and Orbit Toolbox for Matlab. The method used for attitude estimation, Regularized Particle Filter (RPF), is a statistical, brute-force approach to estimation that often works well for problems that are difficult for the conventional Extended Kalman Filter (EKF). Nevertheless, in real time applications its estimation accuracy and efficiency are significantly affected by number of particles which increases the computational overload. The Particle Filter kernel has some similarities with the Unscented Kalman Filter which transforms a set of points (cloud) through known nonlinear equations and combines the results to estimate the mean and covariance of the state. However, in the Particle Filter the points (particles cloud) are chosen randomly, whereas in the Unscented Kalman Filter the points are carefully selected on the basis of a specific criterion. In this way, the number of points used in a Particle Filter generally needs to be much greater than the number of points (called sigma-points) in an Unscented Kalman Filter. The results show that one can reach accuracies in attitude determination within the prescribed requirements using the Regularized Particle Filter, although at extra computational cost when compared to conventional nonlinear filter approaches like EKF.

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A MOTION PLANNING METHOD FOR SPACECRAFT ATTITUDE MANEUVERS USING SINGLE POLYNOMIALS

Albert Caubet* **and James D. Biggs†**

A motion planning technique for generating smooth attitude slew maneuvers is presented, which can generate suboptimal feasible trajectories with low computational cost in the presence of constraints. The attitude coordinates are shaped by time-dependent polynomials, whose coefficients are determined by matching prescribed arbitrary boundary conditions. Quaternions are used as the reference attitude parametrization for arbitrary maneuvers, which require normalization of the four independently shaped coordinates. In the case of spin-to-spin maneuvers, a particular combination of Euler Angles are used. The torque profile is evaluated using inverse dynamics, which allows the feasibility of the maneuver given the actuator constraints to be checked. With this approach, a root-finding method is used to select the minimum time for a certain path. By increasing the degree of the polynomial free coefficients are introduced, thus pointing constraints can be accommodated and time can be optimized amongst this class of motion. This motion planning method is applied to a flexible spacecraft model, demonstrating its effectiveness at reducing spillover vibrations.

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A MICRO-SLEW CONCEPT FOR PRECISION POINTING OF THE KEPLER SPACECRAFT

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Kenneth L. Lebsock[§] and Neil Dennehy[**]

In light of the failure of two of four reaction wheels, the pointing precision of the Kepler spacecraft became so severely degraded that its original mission of hunting planets near the Cygnus constellation could not be continued. Since the scientific instrument remained fully functional, a new mission for Kepler called the K2 mission was proposed. In the K2 mission, Kepler uses a hybrid control architecture for pointing in the ecliptic plane. With the hybrid control architecture, the achievable pointing precision depends on the minimum impulse bit of the spacecraft reaction control system. This paper describes an alternative control strategy called the micro-slew which can be executed with reaction wheels only and used to reduce the control deadband associated with a hybrid control architecture. The new idea may therefore improve the pointing precision of the Kepler spacecraft beyond the K2 mission. The micro-slew concept is based on the observation that the solar radiation pressure acting on Kepler as a disturbance torque can be repurposed as a control torque in order to eliminate reliance on thrusters for three axis control. This is done by designing a three-axis attitude maneuver over small angles (less than 10^{-4} rad) using concepts from optimal control.

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AAS 15-643

HANGING BY A STRING: ATTITUDE CONTROL METHODS AND REACTION WHEEL SIZING ANALYSIS FOR EYASSAT^{3} [*]

Grant M. Thomas,[†] **Daniel R. Jones,**[‡]
Jean-Remy Rizoud[§] **and David J. Richie**[**]

This paper explores using an EyasSAT^{3} CubeSAT as a satellite engineering design and attitude determination and control demonstration tool for Air Force Academy undergraduates. An excellent tool for training future space experts, EyasSAT^{3} contains many standard satellite subsystems and is equipped with twelve photo-resistors, a three-axis magnetometer, and a three-axis rate sensor for attitude determination along with three single-axis torque rods and three reaction wheels for actuation. Interestingly, limitations in the contractor provided hardware have restricted progress thus far, as described in previous work. This effort, therefore, seeks to remedy this condition. More specifically, during reduced order performance testing in late 2014, it became evident the reaction wheel motors have poor control authority, which limits classroom utility. These challenges, then, inspired this effort, which seeks to upgrade the onboard reaction wheel rotor/motor components and improve performance as compared to the existing components. That said, in order to improve satellite tracking performance, this paper assesses three alternative approaches: improving reaction wheel motor performance, decreasing the hamster ball moment of inertia, and improving motor drive software performance. By increasing the EyasSAT^{3} tracking performance, the satellite will more effectively demonstrate the nuances of differing control algorithms to students integrating them in the classroom.

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AAS 15-646

ANALYSIS OF ATTITUDE DYNAMICS OF SPINNING SATELLITES IN AN ELLIPTICAL ORBIT

Dayung Koh* **and Henryk Flashner†**

The attitude dynamics of a spinning satellite in an elliptical orbit subjected on gravity gradient torque is studied. Previous studies mostly assumed small motion dynamics. Consequently, a reliable global behavior of the system was not achieved. In this paper, a new approach that combines analytical and numerical techniques is used to study the global behavior of the full nonlinear system. Families of periodic solutions and rich dynamic phenomena are analyzed. Stability properties and bifurcations of periodic solutions as function of satellite's spin rate and inertia properties are presented. Fast Fourier analysis is utilized to characterize the quasi-periodic behaviors.

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AAS 15-656

GENERALIZED ATTITUDE MODEL FOR MOMENTUM-BIASED SOLAR SAIL SPACECRAFT

Yuichi Tsuda,[*] Go Ono,[†] Kosuke Akatsuka,[‡] Takanao Saiki,[§] Yuya Mimasu,[**] Naoko Ogawa[††] and Fuyuto Terui[‡‡]

This paper describes a method of modeling general attitude dynamics of non-spinning momentum-biased spacecraft under strong influence of solar radiation pressure (SRP). This model, called "Generalized Sail Dynamics Model", can be applied to realistic sails with non-flat surfaces that have non-uniform optical properties. A coarse Sun-pointing, momentum-biased sail spacecraft is especially focused, for which an approximate solution for the equations of motion is analytically derived. Stability and some other fundamental characteristics of momentum-biased sail spacecraft dynamics, as well as theoretical connections with the past representative sail dynamical models are discussed in detail. Furthermore, the unique behaviors predicted by the model are verified using flight data of the Japanese interplanetary probe Hayabusa2.

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AAS 15-685

VELOCITY-FREE ATTITUDE STABILIZATION WITH MEASUREMENT ERRORS

Sungpil Yang,[*] Frédéric Mazenc[†] and Maruthi R. Akella[‡]

This paper addresses the rigid body attitude stabilization problem with the globally nonsingular quaternion representation. Specifically, a passivity-based output feedback controller is considered in the presence of measurement errors. In the absence of uncertainties, it is well known that the body orientation can be stabilized via dynamic extensions in the form of a first-order stable filter from the passivity framework. Once the filter is driven by a noise-corrupted quaternion and the controller employs both the imperfect attitude measurements and the output of the filter, the stability properties of the closed-loop system are weakened. Also, the robustness properties cannot be readily established through the Lyapunov analysis with a typical Lyapunov-like function used for this problem since the time derivative of the function is only negative semi-definite. However, the strictification technique allows us to build a partially strict Lyapunov-like function and eventually to establish certain conditions that guarantee the boundedness of trajectories.

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AAS 15-686

UNIFIED APPROACH TO VARIABLE-STRUCTURE TRACKING CONTROL IN VARIOUS ATTITUDE PARAMETERIZATIONS

Sergei Tanygin[*]

The variable-structure control for attitude tracking is examined in general terms. The earlier developments are placed within the common framework that provides new insights into the effects that different attitude parameterizations have on the closed-loop dynamics. In particular, two alternative sliding mode surfaces are compared: one resulting in the kinematically optimal performance index and the other leading to the linear error dynamics. In previously employed parameterizations, these sliding surfaces differed from each other resulting in controls could attain either the kinematically optimal performance or the linear error dynamics but not both. The analysis carried out in this paper demonstrates how to achieve both objectives using the control written in terms of the rotation vector. The analysis also shows how a similar performance can be realized using the proxy-rotation vector defined from specially tuned generalized Rodrigues parameters.

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AAS 15-687

UNIFIED APPROACH TO ADAPTIVE VARIABLE-STRUCTURE CONTROL FOR ATTITUDE TRACKING IN VARIOUS PARAMETERIZATIONS

Sergei Tanygin[*]

The adaptive variable-structure control for attitude tracking is examined in general terms. The earlier formulation developed in terms of quaternion components is reexamined in a more general form suitable for other attitude parameterizations. The adaptive control laws are modified to address the unwinding phenomenon and to guarantee that the closed-loop error dynamics evolve along the shortest arcs. It is shown that different parameterizations provide additional degrees of freedom for improving parameter adaptation and closed-loop performance.

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NONLINEAR TRACKING ATTITUDE CONTROL OF SPACECRAFT ON TIME DEPENDENT TRAJECTORIES

Ozan Tekinalp,[*] Mohammad M. Gomroki[†] and Omer Atas[‡]

The spacecraft attitude control is carried out using the *to-go* quaternion. A derivative of the *to-go* quaternion is derived where the desired attitude is a time dependent function. Based on this new attitude formulation, a proper state dependent coefficient matrix expression is obtained. Then the nonlinear tracking attitude control is realized using the state dependent Riccati equation method. The simulation results are given and discussed.

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AAS 15-714

FREQUENCY RESPONSE BASED REPETITIVE CONTROL DESIGN FOR LINEAR SYSTEMS WITH PERIODIC COEFFICIENTS

Henry Yau[*] and Richard W. Longman[†]

Repetitive Control (RC) creates control systems that aim to converge to zero tracking error following a periodic command, or aim to completely cancel the effects of a periodic disturbance, e.g. jitter at a fine pointing sensor location caused by imbalance in reaction wheels or CMG's. In some applications, a periodic command can need a nonlinear model. When linearized about the desired output, the equations become linear but with periodic coefficients. This paper develops an RC law for such systems. A previous very effective RC law for constant coefficient systems uses the inverse of the steady state frequency response as a compensator, and results in very fast convergence, often settling within one period plus a fraction. This paper develops the analogous RC law for periodic coefficient models. A mathematical representation of the frequency response inverse for periodic coefficient systems is developed. The law is implemented in the frequency domain, monitoring the frequency components of the error using moving windows of error, and of previous control inputs, computing their frequency contents. Then the change in frequency content needed to create zero tracking error, perhaps with a gain in front, is used to compute the change in the command for the current time step. The algorithm can also handle multiple-input multiple-output systems. An if-and-only-if condition is derived for asymptotic convergence to zero tracking error.

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AAS 15-716

ATTITUDE DYNAMICS MODELING OF SPINNING SOLAR SAIL UNDER OPTICAL PROPERTY CONTROL

Takuro Furumoto,[*] Ryu Funase[†] and Tomohiro Yamaguchi[‡]

Recently, reflectivity control device (RCD) is proposed as a fuel-free attitude control system for spinning sail spacecraft. In this research, an attitude control model for spinning sail spacecraft with reflectivity control capability was derived as an extension of Generalized spinning Sail Model (GSSM). It was found that attitude control capability is determined by three parameters, which depend only on geometric property and optical performance of RCD. The proposed model suggests that the attitude, or the spin axis direction of the sail, converges toward an equilibrium point, which can be controlled within some range determined by the three parameters by switching RCD. Finally, the fidelity of the model was evaluated using actual flight data of IKAROS during RCD operation.

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AAS 15-762

TIME-OPTIMAL REORIENTATION VIA INVERSE DYNAMICS: A QUATERNION AND PARTICLE SWARM FORMULATION

Ko Basu[*] and Robert G. Melton[†]

An inverse-dynamics method is used in conjunction with a particle swarm algorithm to find near-minimum time reorientation maneuvers in the presence of path constraints. The method employs a quaternion formulation of the kinematics, using B-splines to represent the quaternions. The inverse particle swarm optimization provides a method to determine an initial solution for an optimal control problem that may use a gradient-based method. The inverse method provides certain advantages in this problem over a direct method such as enforcement of boundary conditions and the increase of computational efficiency by avoiding the use of numerical integrators.

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AAS 15-772

USING QUADRATICALLY CONSTRAINED QUADRATIC PROGRAMMING TO DESIGN REPETITIVE CONTROLLERS: APPLICATION TO NON-MINIMUM PHASE SYSTEMS

Pitcha Prasitmeeboon* **and Richard W. Longman**†

Repetitive Control (RC) aims for zero tracking error in the presence of a periodic disturbance. Non-minimum phase systems present a difficult design challenge to the sister field of Iterative Learning Control. This paper investigates to what extent the same challenges appear in RC. One challenge is that RC easily handles zeros outside the unit circle in the discrete time *z*-plane introduced by discretization, but the non-minimum phase zeros mapped from continuous time are normally much closer to the unit circle. A second challenge is the result of the small magnitude frequency response at zero frequency produced by the zero. A min-max cost function over the learning rate is presented along with the approach needed to easily compute the optimal solution as a Quadratically Constrained Linear Programming problem. This is shown to be an RC design approach that directly addresses the challenges of non-minimum phase systems. And it has the advantage that it can be designed based on frequency response data directly, without producing a pole-zero system model. But it is shown that this is not the preferred design approach for minimum phase systems. It is demonstrated that the most common approach to RC design, developed by Tomizuka, does not work on non-minimum phase systems. The design based on optimizing the learning rate that the authors advocate for minimum phase systems is seen to give good performance at most frequencies, but require a large number of gains to learn well at DC. One might still want to accept this tradeoff. A new design approach based on Taylor series expansion of the discrete time transfer function is given and shown to be competitive to the min-max approach under appropriate circumstance. The conclusion is that we now have effective methods to design repetitive control of non-minimum phase systems.

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AAS 15-779

SPACECRAFT ATTITUDE DETERMINATION SIMULATION TO IMPROVE THE EFFICIENCY OF A STAR TRACKER

Nathan Houtz[*] and Carolin Frueh[†]

Knowing a spacecraft's orientation is crucial for many of its vital functions. Attitude is often determined using a star tracker. Star tracker attitude determination must be fast and efficient given the limited on board computing resources. To determine its attitude, a star tracker takes an image of its environment, locates the stars in that image, recognizes a pattern among those stars, matches it with patterns in a catalog, and estimates the rotation matrix that relates the spacecraft to the inertial frame. Locating the stars exactly is crucial for the attitude estimation accuracy, however computational efficiency is demanded at the same time. Searching through catalogs to match patterns is a computationally expensive step in this process, too. This work aims to compare the performance of a simple and a high fidelity star location method and provides a potentially more efficient solution to the catalog generation and matching. A new catalog generation method is presented. The new catalog requires over five times as many triangles as existing catalogs and three parameters instead of one, but only 39% as many stars as a reference catalog for a 25° field of view star tracker. Every search performed in the new catalog is guaranteed to find a match. The size of the catalog decreases with larger fields of view, so memory requirements for large field of view start trackers are smaller. The more efficient matching reduces the computational time. Our simulation results are validated with an experimental setup.

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AAS 15-781

ERGODICITY OF THE EULER-POINSOT PROBLEM

Andrew J. Sinclair[*] **and John E. Hurtado**[†]

This paper illustrates the possibility of ergodic motion in the Euler-Poinsot problem. In the traditional polhode/herpolhode interpretation, ergodicity corresponds to a specific location on the polhode never repeating points of contact on the herpolhode. For axisymmetric bodies, this condition corresponds to the commensurability of the radii of the circular polhode and herpolhode. For general asymmetric bodies, the polhode/herpolhode interpretation provides less insight into the nature of the motion. However, recently developed analytic solutions and motion constants provide more direct insight, with ergodicity being related to the commensurability of the periods of the angular-momentum vector and Poinsot's chronometric vector.

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SPACECRAFT GUIDANCE, NAVIGATION AND CONTROL

Session Chairs:

Minh Q. Phan, Dartmouth College
Mark Karpenko, Naval Postgraduate School
David C. Hyland, Texas A&M University
Nathan Strange, Jet Propulsion Laboratory
Daniel Litton, NASA Johnson Space Center
Rees Fullmer, Utah State University
Christopher Roscoe, Applied Defense Solutions
Roberto Furfaro, University of Arizona

The following papers were not available for publication:

AAS 15-517	Paper Withdrawn
AAS 15-589	Paper Withdrawn
AAS 15-654	Paper Withdrawn
AAS 15-703	Paper Withdrawn
AAS 15-707	Paper Withdrawn
AAS 15-711	Paper Withdrawn
AAS 15-751	Paper Withdrawn
AAS 15-801	Paper Withdrawn
AAS 15-814	Paper Withdrawn

POWER STAR^{TM}: A NEW APPROACH TO SPACE SOLAR POWER

David C. Hyland* **and Haithem A. Altwaijry†**

Space Solar Power refers to the concept of a space system that collects solar power via photovoltaics and transmits it to ground collection stations using visible or microwave radiation. Previous system designs developed over the past several decades entail gigantic structures with many moving parts and require on-orbit infrastructure and in-space construction. The concept advanced here combines new solar cell / microwave printing technology with well-established inflatable satellite technology to form a design that has no moving parts, requires no in-space construction and can be packaged in many existing launch vehicle payload fairings.

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AAS 15-529

A MULTILAYER PERCEPTRON HAZARD DETECTOR FOR VISION-BASED AUTONOMOUS PLANETARY LANDING

Paolo Lunghi,[*] Marco Ciarambino[†] and Michèle Lavagna[‡]

A hazard detection and target selection algorithm, based on Artificial Neural Networks, is presented. From a single frame acquired by a VIS camera, the system computes a hazard map, exploited to select the best target, in terms of safety, guidance constraints, and scientific interest. ANNs generalization properties allow the system to correctly operate also in conditions not explicitly considered during calibration. The net architecture design, training, verification and results are critically presented. Performances are assessed in terms of recognition accuracy and selected target safety. Results for different scenarios are discussed to highlight the effectiveness of the system.

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MULTIBODY DYNAMICS DRIVING GNC AND SYSTEM DESIGN IN TETHERED NETS FOR ACTIVE DEBRIS REMOVAL

Riccardo Benvenuto,[*] Samuele Salvi[†] and Michèle R. Lavagna[‡]

Debris removal in Earth orbits is an urgent issue to be faced for space exploitation durability. Among different techniques, tethered-nets present appealing benefits and some open points to fix. Former and latter are discussed in the paper, supported by the exploitation of a multibody dynamics tool. Critical phases as impact and wrapping are analysed to address the tethered-stack controllability: it is shown how the role of contact modelling is fundamental to describe the coupled dynamics: it is demonstrated how friction between the net and a tumbling target allows reducing its angular motion, stabilizing the system and allowing safer towing operations. The critical modes prevention by means of a closed-loop control synthesis is also shown and the connection between flexible dynamics and capture system design is highlighted, giving engineering answers to most challenging open points to lead to a ready to flight solution. Finally, an overview is given on the microgravity test campaign that has been performed to validate the multibody dynamics models.

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AAS 15-547

FEEDBACK TRACKING CONTROL BASED ON A TRAJECTORY-SPECIFIC FINITE-TIME CAUSAL INVERSE

**Nermin Caber,[*] Anil Chinnan,[†] Minh Q. Phan,[‡]
Richard W. Longman[§] and Joachim Horn[**]**

Classical feedback control is typically designed for infinite time with a focus on steady-state performance. However, Iterative Learning Control (ILC) operates in finite time where the same tracking operation is repeated over and over again. This paper develops a finite-time formulation of feedback control based on a trajectory-specific causal inverse that is consistent with the finite-time framework of ILC so that both can later be optimized simultaneously. The performance of the finite-time feedback controller is illustrated on a highly flexible lightly damped dynamical system for tracking a very short trajectory. Disturbance and measurement error are also considered.

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AAS 15-548

THRUST VECTOR CONTROL OF UPPER STAGE WITH UNCERTAINTY OF THE CENTROID

Zhaohui Wang,* Ming Xu,† Lei Jin† and Xiucong Sun*

During the orbit transfer of upper stage, the command direction of thrust vector determined by the guidance system should ideally pass through the centroid when the thruster is working. However, it is hard to realize in actual operation. Moreover, the low identification accuracy of position that leads to the uncertainty of centroid position makes the situation worse. This paper discusses the issue of the thrust vector control (TVC) problem of the upper stage to make sure the thrust vector of the GT passes through the centroid and aligns with the command direction under the uncertainty of centroid. First, a thrust vector control system consisting of the attitude control for the upper stage and the gimbal control of the GT ensures the thrust vector passes through the upper stage's centroid is proposed. Second, a modification procedure is designed to draw the thrust vector aligns with the command direction. The control and modification system can draw the thrust vector tracks the position of the centroid and aligns with the command direction. The validity of the algorithm proposed in this paper is verified by numerical simulations.

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MULTI-CONSTRAINT HANDLING AND A MIXED INTEGER PREDICTIVE CONTROLLER FOR SPACE ROBOTS WITH OBSTACLE AVOIDANCE

Jianjun Luo,[*] Lijun Zong,[†] Baichun Gong[‡] and Jianping Yuan[§]

For the issue that obstacles need to be avoided in many space robots tasks, this paper develops a mixed integer predictive controller for space robots avoiding obstacles when performing tasks. Firstly, an improved obstacle avoidance constraint is formulated based on propositional logic. Then, in the frame of Model Predictive Control (MPC) method, tracking errors and fuel consumptions of all manipulator joints are involved in the cost function, and three types of constraints, joint input and output limits, as well as the developed obstacle avoidance constraint, compose the inequality constraints. Furthermore, the constraint priority is established based on propositional logic, guaranteeing the problem could be solved under the satisfaction of maximum number of the constraints. Simulation results illustrate the improved obstacle avoidance constraint based on propositional logic could be better for particle following the reference trajectory than the traditional one. And the mixed integer predictive controller effectively ensures avoiding obstacles during space robots performing the tasks.

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AAS 15-556

A NOVEL UNIFIED MODELING METHOD AND ADAPTIVE SLIDING MODE CONTROL BASED ON DIFFERENTIAL INCLUSION FOR HYPERSONIC RE-ENTRY VEHICLE

Jianjun Luo,[*] Caisheng Wei,[†] Baichun Gong[‡] and Jianping Yuan[§]

A novel unified modeling approach is proposed to model the multi-model control system for hypersonic re-entry vehicle in wide flight envelope based on differential inclusion. Then based on the unified control model, an adaptive estimator is deigned to estimate the uncertain and un-modeled dynamics parameters. The real-time compensation for the systematic parameters with weight based on coefficient of variation is implemented to prevent the aged model. Afterwards, a modified adaptive nonsingular terminal sliding mode controller by introducing integral sliding mode surface is devised to realize the high precise robust control for hypersonic re-entry vehicle based on the unified control model with parameter dynamic match. Finally, the numerical simulation results verify the efficiency of the modeling approach and controller.

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AAS 15-559

SUPERSPACE AND SUBSPACE INTERSECTION IDENTIFICATION OF BILINEAR MODELS WITH DISCRETE-LEVEL INPUTS

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

When excited by an input consisting of a number of discrete levels, a bilinear system becomes a linear time-varying system whose dynamics switches from one linear subsystem to another depending on the input level. This paper describes an identification method that uses the concept of a superstate of a switched linear system as a superstate of the bilinear system. In a superspace method, these superstates are used directly to identify a bilinear system model. In a subspace intersection method, two or more superstate representations are intersected to find a reduced dimension subspace prior to identification of a bilinear model.

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AAS 15-562

MASS, STIFFNESS, AND DAMPING MATRICES FROM AN IDENTIFIED STATE-SPACE MODEL BY SYLVESTER EQUATIONS

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

This paper presents a method to identify the mass, stiffness, and damping matrices of a dynamical system from an identified state-space model. The solution is decoupled in the sense that the mass, stiffness, and damping matrices are solved from three independent Sylvester equations. Position, velocity, acceleration measurements or any combination can be used. The proposed solution is perhaps the simplest yet, and represents a major improvement over a Kronecker product based solution that is computationally prohibitive for large dimensional problems. The Observer/Kalman filter identification method (OKID) is used as a pre-processing step for optimal identification of a state-space model prior to the recovery of the mass, stiffness, and damping matrices.

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AAS 15-593

A TWO-TIERED APPROACH TO SPACECRAFT POSITIONING FROM SIGNIFICANTLY BIASED GRAVITY GRADIENT MEASUREMENTS

Xiucong Sun,[*] Pei Chen,[†] Christophe Macabiau[‡] and Chao Han[§]

Gravity gradients which can be measured by a spaceborne gradiometer is proposed to provide positioning capabilities for spacecraft in GPS-denied environments. A two-tiered approach is developed to cope with significantly biased measurements. The navigation process consists of a positioning stage and a bias calibration stage. Two different positioning methods are summarized and used in the positioning stage, and a unified covariance analysis is introduced. During the bias calibration stage, the discrete positions are smoothed using orbital dynamics, and biases are estimated from the measurement residuals. The two-tiered approach is tested with GOCE flight data, and steady position errors on the order of 1 kilometer are achieved for both the two methods.

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AAS 15-595

FAST AND EFFICIENT SAIL-ASSISTED DEORBITING STRATEGY FOR LEO SATELLITES IN ORBITS HIGHER THAN 700 KM

Sergey Trofimov[*] and Mikhail Ovchinnikov[†]

A novel efficient deorbiting strategy for LEO satellites is proposed. The attitude motion of a spacecraft with a flat solar sail resembling the Likins-Pringle hyperbolic relative equilibrium can be stabilized by a damping control torque an order of magnitude smaller than the three environmental torques. As a result, there appears a secular decrease of the orbit size induced by solar radiation pressure. For a series of 900 km sun-synchronous orbits with different mean local times of ascending node, numerical simulation of coupled orbit-attitude dynamics reveals a dramatic reduction in deorbit time as compared with the aerostabilized sail deorbiting mode—between 30% at high solar activity and 300% at low solar activity. The smallness of the damping torque required for stabilizing a quasiperiodic attitude motion makes it possible to implement that control even using miniaturized magnetorquers. Sensitivity analysis is conducted with respect to both initial conditions and sailcraft parameters.

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AAS 15-620

AGILITY ENVELOPES FOR REACTION WHEEL SPACECRAFT

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

Spacecraft agility is limited by the maximum torque that reaction wheels can provide. Therefore, a reaction wheel array is typically configured to maximize the inscribed sphere of the reaction wheel torque envelope. However, maximizing the inscribed torque sphere does not, in general, maximize agility. Thus, the industry standard approach can severely underestimate the true capability of an attitude control system. This paper presents the concept of the agility envelope for reaction wheel arrays as a means to identify "hidden agility" that can be exploited to maximize the slew performance of a conventional attitude control system. In a typical example, this hidden agility can be used to reduce slew times without the need for larger, more costly hardware or new control algorithms. Since the agility envelope for a reaction wheel attitude control system is an n-dimensional hypercube projected into three-dimensional space, simple expressions exist for determining the maximal agility envelope. These expressions are developed and used to solve for the limits on angular acceleration and rate for maneuver design and implementation as well as for finding the reaction wheel skew angles that maximize agility for a given spacecraft configuration.

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AAS 15-660

SINGLE-POINT POSITION ESTIMATION IN INTERPLANETARY TRAJECTORIES USING STAR TRACKERS

Daniele Mortari[*] and Dylan Conway[†]

This study provides a closed-form single-point position estimation technique for interplanetary missions using visible planets observed by star trackers. The least-squares solution is obtained by minimizing the sum of the expected object-space squared distance errors. A weighted least-squares solution is provided by an iterative procedure. The weights are evaluated using the distances to the planets estimated by the least-squares solution. It is shown that the weighted approach only requires one iteration to converge and results in significant accuracy gains. The light time correction is taken into account while the stellar aberration cannot be implemented in single-point estimation as it requires knowledge of the velocity. The proposed method is numerically tested in several statistical tests and for one-year interplanetary trajectory example with fixed attitude. The apparent planet magnitudes, the angle between observed visible planets (constrained by the sensor FOV), and the Sun-exclusion angle are computed throughout the trajectory. This study proves that, using a single star tracker pointing to visible planets, it is possible to provide reliable and accurate single-point position estimation in interplanetary missions.

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STATION-KEEPING CONTROL FOR COLLINEAR LIBRATION POINT ORBITS USING NMPC

Chuanjiang Li,[*] Gang Liu,[†] Jing Huang,[‡] Gao Tang[§] and Yanning Guo[**]

A simple station-keeping control strategy for orbits around the colinear libration points in the Earth-Moon system is developed. The motion equations modeled in inertial coordinates with no assumptions is directly employed in the controller design. The proposed control strategy, which is computed using the discrete nonlinear model predictive control theory, is capable of meeting thrust constraints as well as reducing energy consumption. The performance of the proposed strategy has been evaluated by a series of numerical simulations for quasi-periodic orbits derived by a multiple-shooting method in the full ephemeris model.

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OPTIMAL LOW THRUST ORBIT CORRECTION IN CURVILINEAR COORDINATES

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

The minimum-time, constant-thrust transfer between two close, coplanar, quasi-circular orbits is studied using a novel non-linear formulation of relative motion in curvilinear coordinates. The Optimal Control Problem in the thrust orientation angle is treated from a quantitative and qualitative point of view, using the direct and indirect methods respectively. The former yields numerical solutions for a wide range of thrust parameters, while a better understanding of the physics is achieved seeking for an approximate solution of the latter. Fundamental changes in the structure of the solution with the thrust parameter are identified.

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AAS 15-712

RELATIVE OPTICAL NAVIGATION AROUND SMALL BODIES VIA EXTREME LEARNING MACHINES

Roberto Furfaro[*] and Andrew M. Law[†]

To perform close proximity operations under a low-gravity environment, relative and absolute position are vital information to the spacecraft maneuver. Hence navigation is inseparably integrated in space travel. This paper presents Extreme Learning Machine (ELM) as an optical navigation method around small celestial bodies. ELM is a Single Layer feed-Forward Network (SLFN), a brand of neural network (NN). The algorithm based on the predicate that input weights and biases can be randomly assigned and does not require back-propagation. The learned model composes of the output weights which can be used to develop into a hypotheses. The proposed method is used to estimate the position of the spacecraft from optical images obtained through a navigation camera. The results show this approach is promising and potentially suitable for on-board navigation.

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MODIFIED POLYNOMIAL GUIDANCE LAW FOR LUNAR LANDING

Donghun Lee,[*] Jae-Wook Kwon,[*] Hyochoong Bang[†] and Bang-Yeop Kim[‡]

In this paper, a modified polynomial guidance law is studied for a powered terminal descent of a lunar lander. Also, Zero-Effort-Miss/Zero-Effort-Velocity (ZEM/ZEV) and modified Apollo guidance laws including off-line trajectory optimization approach are analyzed. Because each guidance law has advantages and drawbacks, modified polynomial guidance law is proposed. The modified guidance law is derived quasi-analytically after taking advantages of previous real-time guidance laws for onboard application. In the numerical simulation section, performance will be compared from several points of view such as avoiding surface collision and fuel consumption.

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CUBESAT PROXIMITY OPERATIONS DEMONSTRATION (CPOD) MISSION: END-TO-END INTEGRATION AND MISSION SIMULATION TESTING

Christopher W. T. Roscoe,[*] Jason J. Westphal,[*]
Christopher T. Shelton,[†] and John A. Bowen[‡]

The CubeSat Proximity Operations Demonstration (CPOD) mission will demonstrate rendezvous, proximity operations, and docking with a pair of 3U CubeSats using miniaturized components and sensors. The goal of this mission is to develop small spacecraft technologies with game-changing potential and validate these technologies via spaceflight. Several new systems have been designed specifically for this program, including: next generation star trackers, next generation miniature reaction wheels, miniature cold-gas multi-thruster propulsion modules, a new relative navigation sensor suite, power management and distribution electronics based on flight proven designs, and intelligent software solutions hosted on multiple low-power Linux ARM processors. This paper presents a brief overview of the CPOD spacecraft and the mission Concept of Operations (ConOps) and detailed description of the recent end-to-end integration and mission simulation testing campaign. The test campaign demonstrates the readiness of the integrated system in support of the flight mission.

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OPTIMIZED FINITE-TIME FEEDBACK AND ITERATIVE LEARNING CONTROL DESIGN

Anil Chinnan,[*] Minh Q. Phan[†] and Richard W. Longman[‡]

Simultaneous design of feedback and learning controllers is highly desirable for tracking trajectories that are short relative to the settling time of the system. This paper formulates a method to design both the feedback controller and learning controller by minimizing a quadratic cost function. The cost function includes terms that weigh the overall tracking error, feedback tracking error, magnitude of the feedback gains, and magnitude of the update to the learning signal. In order to avoid non-linearity in the optimization, caused by working with the feedback gains directly, the feedback controller is designed through an intermediate matrix. The matrix Q can be interpreted as a causal inverse matrix for a specific or a family of finite-time trajectories and/or disturbances. While updating the feedback gains and learning signals from repetition to repetition, the Q matrix can be held static as initially designed or allowed to be adaptive. The combined feedback and learning design is illustrated on an extremely lightly damped, flexible system, where the duration of the desired trajectory to be tracked is approximately one-twentieth of the settling time of the system.

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AAS 15-732

DIRECT POSITIONING AND AUTONOMOUS NAVIGATION ALGORITHM BASED ON DUAL CONE-SCANNING HORIZON SENSOR/STAR SENSOR

**Weihua Ma,[*] Jinwen Tan,[†] Malcolm Macdonald,[‡]
Baichun Gong[§] and Jianjun Luo[**]**

One method using the pure attitude sensors, Infrared Scanning Horizon Sensors (ISHS) and Star Sensor (SS), to determine the absolute position in inertial frame is developed. With the absolute position from the ISHS/SS, the Autonomous Integrated Navigation System (AINS) filter could be simplified. Based on the common nadir vectors from ISHS and absolute attitude from SS, a new direct positioning algorithm for ISHS/SS is constructed. The positioning error model is derived, too. Different the common method using the nadir vector/angle of ISHS to construct the observation, the inertial position from ISHS/SS is chosen as the observation of the AINS filter to estimate the absolute position and velocity. The Jacobin matrix of observation equation could be simplified greatly because the observation would not include the complex trigonometric function caused by the nadir vector/angle of ISHS. Simulation with the data from STK validates the correction of the direct positioning algorithm of ISHS/SS and the corresponding error model. The new AINS filter is tested to be convergence. The AINS position and velocity precision is about 500m (3σ) and 0.5m/s (3σ) if the measurement precision of ISHS and SS are 0.1° (3σ) and 0.005° (3σ), respectively.

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AAS 15-736

AUTONOMOUS OBSERVATION PLANNING WITH FLASH LIDAR AROUND SMALL BODIES

Ann Dietrich[*] **and Jay W. McMahon**[†]

A flash LIDAR instrument, which returns a three-dimensional image of its subject, is investigated here for spacecraft autonomous navigation. Previous work found this instrument can provide high accuracy for navigation; however processing power was large. This study investigates the navigation capabilities of flash LIDAR and techniques to reduce processing power. Image characteristics such as edge detection or the area of an object within the image are quick to compute and can aid in determining an initial estimate of the spacecraft to initialize the filter. Once the filter is running, observation planning algorithms developed here maximize the information content of a subset of image pixels through the Fisher Information Matrix, and reduce processing power while still providing an accurate state estimate. The combination of these methods establishes a framework in which a spacecraft could autonomously determine its position from minimal state-knowledge to sub-meter position accuracy using flash LIDAR measurements.

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AAS 15-737

LAUNCH RESULTS OF GUIDANCE & CONTROL SYSTEM OF EPSILON ROCKET

**Hirohito Ohtsuka,[*] Yasuhiro Morita,[†] Kensaku Tanaka,[*]
Takanao Saiki,[†] Takayuki Yamamoto,[†] Hiroyuki Yamaguchi,[†]
Yasunobu Segawa[*] and Hitomi Gotoh[*]**

The first Epsilon rocket was launched successfully with a small payload 'HISAKI' on September 14th, 2013 in Japan. Epsilon has a new absorber structure in Payload Attach Fitting to reduce the vibration condition for payload. We designed the robust control logic to satisfy the compatibility of robust stability and response against various disturbances. The 3rd Stage under spinning has a Rhumb-line Control function which reduces the pointing error at separation and ignition of solid motor. We could insert the payload into the orbit precisely by 'LVIC' guidance, suitable for low thrust propulsion in Post Boost Stage. We will present the flight results of the Guidance & Control (G&C) system and dynamics of Epsilon rocket.

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IMAGE PROCESSING OF EARTH AND MOON IMAGES FOR OPTICAL NAVIGATION SYSTEMS

Stoian Borissov[*] and Daniele Mortari[†]

This paper presents a summary of methods for processing real and synthetic images of the Moon and Earth for the purposes of Optical Navigation of spacecraft. They were developed in order to comply with autonomous navigation capabilities requirements for NASA's Orion missions, however their application may be applied to a broad range of optical navigation problems. Using a pinhole camera taking images of a celestial body the image processing provides estimate of the observer position using knowledge of time, attitude, camera parameters, and a rough estimation of the observer position to identify the body observed and the sun illumination. Image processing follows a multi-step process which produces an estimate for the relative position between observer and observed body. Preliminary steps remove image distortion and select high contrast pixel from the gradient of the image. Then, edge detection schemes attempt to select only pixels belonging to the edge of the target body and use those pixels to obtain a first estimation of body centroid and distance. This estimation is then refined using a 2-Dimensional model (Gaussian) modeling the gradient behavior of a set of pixels selected around the illuminated hard edge. These methods have been applied to synthetic images generated using the NASA's EDGE software as well as to real images of the Moon taken from on board the ISS by a Nikon camera. Results from each of the image sets are presented and the strengths of the algorithm are evaluated against the Orion mission requirements. Areas of future work are suggested as well.

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AAS 15-754

NEURAL NETWORK BASED ADAPTIVE CONTROLLER FOR ATTITUDE CONTROL OF ALL-ELECTRIC SATELLITES

Suwat Sreesawet,[*] Venkatasubramani S. R. Pappu,[†]
Atri Dutta[‡] and James E. Steck[§]

This paper considers the attitude control problem for an all-electric spacecraft during its transfer to the Geostationary Earth orbit. During the transfer, the spacecraft's solar arrays need to point towards the Sun, except in eclipses, in order to operate the onboard electric thrusters. We propose a neural-network based adaptive controller, utilizing a Modified State Observer (MSO) methodology, for the attitude control of the all-electric spacecraft. The MSO generates adaptations to aid a traditional PD controller in tracking the commanded attitude and angular velocity, while the adaptive controller use the state estimation error (instead of the tracking error) to account for the uncertainties. Numerical simulations illustrate the performance of the proposed controller for cases of changing spacecraft moment of inertia due to fuel burn, the presence of a disturbing torque due to thruster misalignment and lack of attitude tracking during eclipses.

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AAS 15-771

ATTITUDE DYNAMICS OF A NEAR-SYMMETRIC VARIABLE MASS CYLINDER

Angadh Nanjangud[*] and Fidelis O. Eke[†]

This paper examines the attitude motion of a near-symmetric cylinder with uniform mass loss. Since the fundamental equations governing the motion of a near-symmetric system are typically non-linear, it is often difficult, or even impossible, to generate analytical solutions. In this paper, an approximation approach to linearize the equations of motion for a class of such systems to obtain analytical solutions is presented. Results from the approximate analytical solution and the numerical simulation of the exact nonlinear equations of attitude motion are contrasted and a simplification to the linear model is briefly explored.

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AAS 15-777

SATELLITE MAGNETISM: TORQUE RODS FOR EYASSAT^3 ATTITUDE CONTROL*

David J. Richie,† Maxime Smets,‡ Jean-Christophe Le Roy,‡
Michael Hychko§ and Jean-Remy Rizoud**

Often considered only for satellite reaction wheel desaturation, when employed correctly, torque rods are an effective, independent means of satellite pointing control: both on orbit and in the classroom. In fact, the US Air Force Academy has recently developed a CubeSat classroom demonstrator known as EyasSat^3, complete with reaction wheels, light detecting photo-resistors, a magnetometer, and three-axis magnetic torque rods as well as several other attitude control sensor and actuator systems. Previous papers have investigated these EyasSat^3 systems, but none, including the contractor through its provided documentation, have focused on the EyasSat^3 predicted and demonstrated torque rod performance with and without the one-axis Helmholtz cage, an effective method to control the background magnetic field in laboratory (thus classroom) conditions. In this work, spacecraft attitude dynamics, magnetic field dynamics, and magnetic actuation fundamental principles, torque rod and Helmholtz cage hardware sizing, and the resulting EyasSat^3 performance are presented. The benefits are wide reaching as this simple, yet effective demonstration technique gives tomorrow's leaders, including Academy cadets, a hands-on learning experience that will shape their mastery of key attitude control principles.

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AAS 15-782

DETECTION STRATEGIES FOR HIGHRATE, LOW SNR STAR DETECTIONS

Laila Kazemi,[*] John Enright[†] and Tom Dzamba[‡]

We present an assessment of various image thresholding and centroiding algorithms to improve star tracker centroiding accuracy at moderate slew rates (< 10° / s). This work presents an image processing algorithm for star images that preserves star tracker detection accuracy and is able to detect dim stars up to slew rates less than 10° / s. Most star detection algorithms in literature are designed to work in stationary imaging conditions. In this study we explore the algorithmic tradespace for detecting dim elongated stars. The primary factors we consider are: the detection strategy and the sensitivity to exposure time. The performance of the algorithms are assessed using simulations and lab testing. The primary performance metrics are false positive ratio, and false negative ratio of star pixels. We introduced a new algorithm for star detection in moderate slew rates that increases the star detection accuracy in moderate slew rates and it is robust to stray light.

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CIRCULANT ZERO-PHASE LOW PASS FILTER DESIGN FOR IMPROVED ROBUSTIFICATION OF ITERATIVE LEARNING CONTROL

Bing Song[*] and Richard W. Longman[†]

Iterative learning control can produce zero tracking error to a command that is repeated, each time starting from the same initial condition. Spacecraft applications include repeated scanning maneuvers with fine pointing equipment. A zero-phase frequency cutoff of the learning is usually needed to robustify to residual modes or parasitic poles. Because ILC is a finite time problem, and frequency response is a steady state property, there is some mismatch when using normal frequency cutoff. A zero-phase Butterworth filter needs initial conditions specified at the start and at the end of the time interval. These produce transients at both beginning and end of the trajectory that are not related to the filter robustification objective. It is demonstrated that these issues in the Matlab filtfilt function can produce instability of the learning process. This paper presents a different approach for ILC that designs a zero phase filter using a circulant matrix and prescribes a reflected extension of the signal to be filtered. The approach makes the finite time filter represent the true desired steady state frequency response behavior, it eliminates the mismatch, eliminates the issues associated with choice of initial conditions and resulting transients, and eliminates the instability issue. Similar cliff filter designs are also considered.

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INCORPORATING ANGULAR RATE SENSORS FOR DERIVATIVE CONTROL OF AN EDUCATIONAL CUBESAT[*]

Brian W. Kester,[†] Richard Phernetton,[‡] A. Saravanan,[§]
Lim Wei Shen Noel[§] and David J. Richie[**]

The United States Air Force Academy's EyasSat^3 is a low cost platform aimed at providing students with hands-on experience in satellite subsystem design as a part of an integrated space systems engineering curriculum. In previous work a single-axis controller was developed for EyasSat^3 using photocell sensors and reaction wheels to orient the spacecraft toward a light source and follow it, but transient response to a step input yielded poor overshoot performance. One method for improving transient response is by providing derivative feedback and direct derivative feedback can be obtained via an angular rate sensor. When initially employed on EyasSat^3, the angular rate sensors provided unreliable measurements and needed to be characterized and corrected. This paper outlines the basic implementation of the single-axis controller and describes the efforts to correct the on-board angular rate sensors, culminating in a software solution to the problem. The single axis controller provides a baseline for future 3-axis control design and provides critical sensor and actuator characterizations to be used in upcoming control strategies.

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SOLAR SAIL SPACECRAFT BOOM VIBRATION DURING DEPLOYMENT AND DAMPING MECHANISMS

Omer Atas,[*] Ertan Demiral[†] and Ozan Tekinalp[‡]

Boom deployment vibration analysis is presented for a solar sail 3U Cubesat. The damping of the boom vibration using shape memory alloys is examined. It is found that shape memory alloys do not reduce vibration below a certain level. Vibration damping via inherent friction in the deployment system is also considered. The analysis showed that the vibration may be completely damped due to the inherent friction in the deployment system.

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AAS 15-804

SINGULARITY ANALYSIS OF CONTROL MOMENT GYROS ON GYROELASTIC BODY

Quan Hu,[*] Yao Zhang,[†] Jingrui Zhang[‡] and Zixi Guo[§]

Control moment gyro (CMG) is a widely used device for generating control torques for spacecraft attitude control without expending propellant. Because of its effectiveness and cleanness, it has been considered to be mounted on a space structure to achieve vibration suppression. The resultant system is the so-called *gyroelastic body*, on which the CMGs could exert both torques and modal forces. Therefore, the CMGs can be used to simultaneously achieve attitude maneuver and vibration reduction of a flexible spacecraft. In this paper, we consider the singularity problem in such an application of CMGs. The dynamics of an unconstrained gyroelastic body is established, from which the output equation of the CMGs is extracted. Then, torque singular state and modal force singular state are defined and visualized to demonstrate the singularity problem. Numerical examples of several typical configuration on a gyroelastic body are given. Finally, a steering law allowing output error is designed.

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AAS 15-810

RANDOM MATRIX BASED APPROACH TO QUANTIFY THE EFFECT OF MEASUREMENT NOISE ON MODEL IDENTIFIED BY THE EIGENVALUE REALIZATION ALGORITHM

Kumar Vishwajeet,[*] Puneet Singla[†] and Manoranjan Majji[‡]

This paper focuses on the development of analytical methods for uncertainty quantification of system matrices obtained by the Eigenvalue Realization Algorithm (ERA) to quantify the effect of noise in the observation data. Starting from first principles, analytical expressions are presented for the probability density function for norm of system matrix by application of standard results in random matrix theory. Assuming the observations to be corrupted by zero mean Gaussian noise, the distribution for the Hankel matrix is represented by the non-symmetric Wishart distribution. From the Wishart distribution, the joint density function of the singular value of the Hankel matrix are constructed. These expressions enable us to construct the probability density functions for the norm of identified system matrices. Numerical examples illustrate the applications of ideas presented in the paper.

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AAS 15-813

AFFINE INVARIANT TRACKING OF IMAGE FEATURES UTILIZING IMU DATA

Brian Bergh,[*] Manoranjan Majji[†] and Xue Iuan Wong[*]

Feature extraction and tracking methods that incorporate relative pose estimates of the camera system are presented in this paper. It is anticipated that, by accounting for the rigid motion parameters sensed independently by an inertial measurement unit (or a star camera), better characterization of the optical flow of the image features can be accomplished (i.e., sensor fusion). We leverage the first order effects incurred by the optical flow to improve the performance of feature tracking algorithms. Starting from first principles, a systematic approach is provided in this paper to provide first order estimates of the affine deformations incurred by the imaging process due to the rigid body motions of the sensor platform. In addition to capturing view-point variations, three additional parameters are introduced in the image plane deformation model to capture the effects of illumination variations and image scale. The key developments of this theory affect all aspects of photogrammetry and vision based relative navigation, useful in spacecraft proximity operations.

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AAS 15-816

GENERALIZED MOMENTUM CONTROL OF THE SPIN-STABILIZED MAGNETOSPHERIC MULTISCALE FORMATION

Steven Z. Queen,[*] Neerav Shah,[*] Suyog S. Benegalrao[*]
and Kathie Blackman[†]

The Magnetospheric Multiscale (MMS) mission consists of four identically instrumented, spin-stabilized observatories elliptically orbiting the Earth in a tetrahedron formation. The on-board attitude control system adjusts the angular momentum of the system using a generalized thruster-actuated control system that simultaneously manages precession, nutation and spin. Originally developed using Lyapunov control-theory with rate-feedback, a published algorithm has been augmented to provide a balanced attitude/rate response using a single weighting parameter. This approach overcomes an orientation sign-ambiguity in the existing formulation, and also allows for a smoothly tuned-response applicable to both a compact/agile spacecraft, as well as one with large articulating appendages.

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TRAJECTORY DESIGN AND OPTIMIZATION

Session Chairs:

Kohei Fujimoto, Utah State University
David B. Spencer, Pennsylvania State University
Roby Wilson, Jet Propulsion Laboratory
Jacob Williams, NASA Johnson Space Center
Ryan Whitley, NASA Johnson Space Center
Thomas Carter, Eastern Connecticut University
Christopher Spreen, Purdue University
Renato Zanetti, NASA Johnson Space Center
Jeffrey Stuart, Jet Propulsion Laboratory
Alfred Lynam, West Virginia University
Ryan P. Russell, The University of Texas at Austin

The following papers were not available for publication:

AAS 15-501	Paper Withdrawn
AAS 15-625	Paper Withdrawn
AAS 15-671	Paper Withdrawn
AAS 15-698	Paper Withdrawn
AAS 15-708	Paper Withdrawn
AAS 15-800	Paper Withdrawn

AAS 15-507

IMPULSIVE HALO TRANSFER TRAJECTORY DESIGN AROUND SEL1 POINT WITH MULTIPLE CONSTRAINTS

Hao Zeng,[*] Jingrui Zhang,[†] Mingtao Li[‡] and Zixi Guo[§]

Many plans have been proposed which aim to take advantage of the growing scientific interest in the region of space near Sun-Earth/Moon libration points. This paper provides a method to design of transfers from LEOs to Sun-Earth / Moon L1 halo orbits with multiple constraints, which include orbital radius, orbit inclination, right ascension of ascending node (RAAN) and track angle. The methodology includes differential correction and initial value expression that deal with the initial guesses of differential correction. Meanwhile, in view of multiple solution problems of RAAN in different launch epoch, a relationship between launch epoch constraint and RAAN constraint is introduced to guarantee convergence of the algorithm. Finally, using the methodology, impulsive transfer trajectory from a 200km Earth parking orbit to SEL1 point orbit is designed with multi-restriction on different launch sites. Additionally, finding similar solutions with launches in different months is obtained to expand the launch opportunities.

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LISA PATHFINDER – ROBUST LAUNCH WINDOW DESIGN FOR A TRANSFER TOWARDS A LARGE AMPLITUDE ORBIT ABOUT THE SUN-EARTH LIBRATION POINT 1

Florian Renk,* Bram de Vogeleer† and Markus Landgraf‡

The LISA Pathfinder mission is scheduled for launch in the fourth quarter of 2015. The operational orbit of LPF has been chosen to be a large amplitude quasi-Halo orbit about the Sun-Earth Libration Point 1. The launch will be from Kourou, French Guyana, on Europe's small payload VEGA launcher. The performance of the VEGA does not allow for a direct injection towards the Sun-Earth Libration Point region, but only allows for an injection onto a near equatorial eccentric orbit with 1539 km x 207 km apogee and perigee altitude, respectively. Consequently LPF must propel itself towards its operational orbit. This injection cannot be done in one manoeuvre without accepting significant gravity loss. Thus, during the launch and early operations phase (LEOP) a sequence of several apogee raising manoeuvres is required to finally inject LPF onto the stable manifold of a suitable libration point orbit. During this phase the S/C will travel through the radiation belts several times and thus the optimization of the apogee raising sequence will not only require a minimization of the transfer ΔV, but it will also require a minimization of the radiation dose to protect the sensitive payload. To allow for a robust transfer design the launch window calculations must allow for several failure scenarios during this critical LEOP. The global optimization requirements to obtain a ΔV, radiation and contingency optimal apogee raising sequence will be introduced and the results of the optimization will be discussed. It will also describe how the daily launch times will be selected in order to cover as many contingency cases as possible and potential recovery strategies. The paper will also introduce the required transfer navigation after the separation of the science module from the payload module, since the science module is equipped with low thrust cold gas propulsion only, which in addition only allows thrusting into the Sun directions.

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AAS 15-522

TRAJECTORY DESIGNS FOR A MARS HYBRID TRANSPORTATION ARCHITECTURE

Min Qu,[*] Raymond G. Merrill,[†] Patrick Chai[‡] and David R. Komar[§]

NASA's Human spaceflight Architecture Team (HAT) team is developing a re-usable hybrid transportation architecture in which both chemical and electric propulsion systems are used to send crew and cargo to Mars destinations such as Phobos, Deimos, the surface of Mars, and other orbits around Mars. By combining chemical and electrical propulsions into a single spaceship and applying each where it is the most effective, the hybrid architecture enables a series of Mars trajectories that are more fuel-efficient than an all chemical architecture without significant increases in flight times. This paper documents the methods and techniques used for the trajectory designs of the architecture, some of which have shown to provide propellant or delta-V savings over traditional methods.

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AAS 15-523

MULTI-OBJECTIVE HYBRID OPTIMAL CONTROL FOR MULTIPLE-FLYBY INTERPLANETARY MISSION DESIGN USING CHEMICAL PROPULSION

Jacob A. Englander,[*] Matthew A. Vavrina[†] and David Hinckley Jr.[‡]

Preliminary design of high-thrust interplanetary missions is a highly complex process. The mission designer must choose discrete parameters such as the number of flybys and the bodies at which those flybys are performed. For some missions, such as surveys of small bodies, the mission designer also contributes to target selection. In addition, real-valued decision variables, such as launch epoch, flight times, maneuver and flyby epochs, and flyby altitudes must be chosen. There are often many thousands of possible trajectories to be evaluated. The customer who commissions a trajectory design is not usually interested in a point solution, but rather the exploration of the trade space of trajectories between several different objective functions. This can be a very expensive process in terms of the number of human analyst hours required. An automated approach is therefore very desirable. This work presents such an approach by posing the impulsive mission design problem as a multi-objective hybrid optimal control problem. The method is demonstrated on several real-world problems.

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AAS 15-543

TRAJECTORY OPTIMIZATION FOR LOW-THRUST MULTIPLE ASTEROIDS RENDEZVOUS MISSION

Gao Tang,[*] Fanghua Jiang[†] and Junfeng Li[‡]

A mission designed to rendezvous with a dozen asteroids in the Main-Belt with low-thrust propulsion within a preset duration is investigated. Indirect methods with homotopic approaches and switching moments detection methods are implemented to optimize the low-thrust trajectories. Optimization of low-thrust trajectories between two asteroids is derived first. With fixed initial and terminating moments, the utilization of homotopic approach provides a fast method to obtain an approximation even with random guesses. To further improve the efficiency to optimize low-thrust transfers between low-inclination low-eccentricity orbits, an effective method is proposed to help providing initial guesses. To optimize the low-thrust trajectory to rendezvous with a dozen asteroids in whole, the conditions for optimality are concluded which are used to build the shooting function. The method to split the trajectory into several segments and solve them sequentially is applied first. Then the results obtained in the last step are used to provide initial guesses to optimize the low-thrust transfers in whole. The method to use them is proposed with some basic derivations. Finally the homotopic form is removed and the bang-off-bang control is directly solved. Numerical examples where three sequences containing a dozen asteroids are optimized demonstrates the validity of these methods.

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AAS 15-552

MISSION ANALYSIS FOR A HUMAN EXPLORATION INFRASTRUCTURE IN THE EARTH-MOON SYSTEM AND BEYOND

Florian Renk[*] and Markus Landgraf[†]

In the frame of the International Space Exploration Coordination Working Group (ISECG) the European Space Agency (ESA) is participating in the planning of future exploration architectures. This participation also puts new challenges on the mission analysis of such architectures, since the mission analysis for an exploration architecture design is significantly different from the one of a single mission design. It is the intention of this paper to foster the discussion and exchange on the link between architecture design and trajectory design rather than providing a scientific contribution to trajectory design. While the focus is currently on lunar exploration, the access to future destinations as e.g. the Sun-Earth Libration Point region as well as interplanetary departures towards asteroids and Mars may not be neglected. In the paper features that are relevant to a likely human-robotic partnership scenario of a space exploration architecture are discussed. The goal of the mission analysis must be to support the architecture analysts in finding an optimal solution considering the possible contributions of all international partners. While this might be sub-optimal from a single mission design perspective, a possible redundancy by choosing a specific mission scenario could greatly mitigate the operational and programmatic risk while enhancing the stainability of the overall design. One of the key areas will be the investigations of the Earth-Moon Libration Points as staging locations. Other staging locations which have been proposed are the Low Lunar Orbits (LLO)s and the distant retrograde orbits (DRO)s, the latter ones already foreseen as destinations for the asteroid retrieval mission and the second operational demonstration (EM-2) mission of the Orion vehicle (the first crewed mission). The paper gives an overview of existing research on some of the topics, the currently known pros and cons of the options and will explain on which aspects of the system engineering, architecture engineering as well as the mission analysis the focus is currently put on.

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AAS 15-580

TARGETING THE MARTIAN MOONS VIA DIRECT INSERTION INTO MARS' ORBIT

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

Here, we analyze interplanetary transfer maneuvers from Earth to Mars in order to target the Martian moons, Phobos and Deimos. Such analysis is done by solving Lambert's Problem and investigating the necessary targeting upon arrival at Mars. Additionally, the orbital parameters of the arrival trajectories as well as the relative required Δv's and times of flight were determined in order to define the optimal departure and arrival windows for a given range of dates. It was found that minimum Δv trajectories for Earth-Phobos and Earth-Deimos transfers do not necessarily occur when Δv for Earth-Mars transfers is minimized, but they depend on the orientation of the arrival orbit and the type of maneuver that is performed to rendezvous with one of the Martian moons.

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AAS 15-582

GLOBAL OPTIMIZATION OF INTERPLANETARY TRAJECTORIES IN THE PRESENCE OF REALISTIC MISSION CONSTRAINTS

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

Interplanetary missions are often subject to difficult constraints, like solar phase angle upon arrival at the destination, velocity at arrival, and altitudes for flybys. Preliminary design of such missions is often conducted by solving the unconstrained problem and then filtering away solutions which do not naturally satisfy the constraints. However this can bias the search into non-advantageous regions of the solution space, so it can be better to conduct preliminary design with the full set of constraints imposed. In this work a stochastic global search method is developed which is well suited to the constrained global interplanetary trajectory optimization problem.

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AAS 15-585

EFFICIENT MANEUVER PLACEMENT FOR AUTOMATED TRAJECTORY DESIGN

Damon Landau[*]

When designing a mission, the addition of a maneuver at the right spot often improves the utility of an otherwise mediocre trajectory. However, the additional degrees of freedom of finding the best maneuver location can severely complicate automated broad-search algorithms. A computationally-efficient formulation that reduces the maneuver design space to a single dimension is presented, where the efficacy of additional maneuvers along previously computed transfers is calculated explicitly via Lawden's "primer vector." Examples include leveraging maneuvers to ease capture at Europa, phasing maneuvers to enable resonant-hopping among Saturn's moons, and broken-plane maneuvers on transfers to Mars.

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AAS 15-588

EARTH-MARS TRANSFERS THROUGH MOON DISTANT RETROGRADE ORBIT

Davide Conte,[*] Marilena Di Carlo,[†] Koki Ho,[‡]
David B. Spencer[§] and Massimiliano Vasile[**]

This paper focuses on trajectory design which is relevant for missions that would follow NASA's Asteroid Redirect Mission (ARM) to further explore and utilize asteroids and eventually human Mars exploration. Assuming that a refueling gas station is present at a given Lunar Distant Retrograde Orbit (DRO), we analyze ways of departing from the Earth to Mars via that DRO. Thus, the analysis and results presented in this paper add a new cis-lunar departure orbit for Earth-Mars missions. Porkchop plots depicting the required C_3 at launch, v_∞ at arrival, Time of Flight (TOF), and total ΔV for various DRO departure and Mars arrival dates are created and compared with results obtained for low ΔV LEO to Mars trajectories. The results show that low ΔV DRO to Mars transfers generally have lower ΔV and TOF than LEO to Mars maneuvers.

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MANY-REVOLUTION LOW-THRUST ORBIT TRANSFER COMPUTATION USING EQUINOCTIAL Q-LAW INCLUDING J_2 AND ECLIPSE EFFECTS

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

Mission designers addressing the computation of low-thrust many-revolution transfers need versatile and reliable tools for solving the problem with efficient computational times. This paper proposes a Lyapunov feedback control method, Q-law by Petropoulos with algorithm modifications to accommodate for the singularities in the original equations and to include the most relevant perturbations, such as the J_2 perturbation and the effect of coasting during eclipse periods. The optimization of the control-law parameters via a multi-objective evolutionary algorithm (NSGA-II) improves the results significantly and permits to easily compute the minimum time transfer and a well-spread Pareto front, trading transfer time versus propellant.

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AAS 15-591

OPTIMIZING THE SOLAR ORBITER 2018 OCTOBER TRAJECTORY TO INCREASE THE DATA RETURN

José M. Sánchez Pérez,[*] Waldemar Martens[†] and Yves Langevin[‡]

The ESA-NASA Solar Orbiter mission has recently shifted the launch date to October 2018. Further analysis of the planned trajectory has revealed an inferior data downlink capability than all previous trajectories regarded for the mission. Being the data bit rate inversely proportional to the square of the Earth distance, it becomes critical to phase the science orbit such that several aphelia are close to the Earth providing extended periods with maximum downlink capability. This paper describes alternative trajectories that improve significantly the data return overall for the mission and also in particular reaching an improvement factor of 2 during the core science period.

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AAS 15-594

ANALYTICAL LOW-THRUST TRANSFER DESIGN BASED ON VELOCITY HODOGRAPH

D. J. Gondelach* and R. Noomen†

Shape-based models can be used to approximate low-thrust transfer orbits between celestial bodies. Here, a new model is proposed, which is based on simple analytical base functions that together represent the velocity of the spacecraft. After integration, these base functions also yield analytical expressions for distances traveled. As a result, both the velocity and the trajectory of a transfer can be modeled analytically with a series of such base functions, which can be chosen and scaled at will. Constraints (*i.e.* conditions on initial and final position and velocity) can be satisfied directly, and a constraint on the final polar angle can be met with a straightforward, fast numerical integration. The technique allows for direct solutions with no degrees of freedom, but also facilitates a more extensive analytical modeling where certain aspects of the resulting transfer trajectory (*e.g.* required ΔV, maximum acceleration) can be optimized. The main characteristics of the technique are illustrated in a number of cases: transfers to Mars and Mercury.

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AAS 15-598

IDENTIFYING ACCESSIBLE NEAR-EARTH OBJECTS FOR CREWED MISSIONS WITH SOLAR ELECTRIC PROPULSION

Stijn De Smet,[*] Jeffrey S. Parker,[†] Jonathan F. C. Herman,[*] Jonathan Aziz,[*] Brent W. Barbee[‡] and Jacob A. Englander[‡]

This paper discusses the expansion of the Near-Earth Object Human Space Flight Accessible Targets Study (NHATS) with Solar Electric Propulsion (SEP). The research investigates the existence of new launch seasons that would have been impossible to achieve using only chemical propulsion. Furthermore, this paper shows that SEP can be used to significantly reduce the launch mass and in some cases the flight time of potential missions as compared to the current, purely chemical trajectories identified by the NHATS project.

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AAS 15-600

PERIAPSIS POINCARÉ MAPS FOR PRELIMINARY TRAJECTORY DESIGN IN PLANET-MOON SYSTEMS

Diane C. Davis,[*] Sean M. Phillips[†] and Brian P. McCarthy[‡]

Spaceflight in regimes where multiple gravitational bodies simultaneously affect a spacecraft trajectory is increasingly common. However, preliminary trajectory design in the presence of two or more large bodies is challenging due to the complicated nature of such orbits. In this investigation, periapsis Poincaré maps are employed to characterize the design space in the vicinity of planetary moons. Using an interactive visualization tool, initial conditions are easily selected to satisfy a variety of mission applications in multibody systems. In particular, long-term orbits around the smaller primary in planet-moon systems are considered.

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AAS 15-606

A NEW ARCHITECTURE FOR EXTENDING THE CAPABILITIES OF THE COPERNICUS TRAJECTORY OPTIMIZATION PROGRAM

Jacob Williams[*]

This paper describes a new plugin architecture developed for the Copernicus spacecraft trajectory optimization program. Details of the software architecture design and development are described, as well as examples of how the capability can be used to extend the tool in order to expand the type of trajectory optimization problems that can be solved. The inclusion of plugins is a significant update to Copernicus, allowing user-created algorithms to be incorporated into the tool for the first time. The initial version of the new capability was released to the Copernicus user community with version 4.1 in March 2015, and additional refinements and improvements were included in the recent 4.2 release. It is proving quite useful, enabling Copernicus to solve problems that it was not able to solve before.

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AAS 15-607

UNSCENTED OPTIMIZATION

I. Michael Ross,[*] Ronald J. Proulx[†] and Mark Karpenko[‡]

Unscented optimization combines the concept of the unscented transform with standard optimization to produce a simple technique for mitigating the effect of uncertainties. This new approach addresses some long-standing challenges in practical probabilistic programming by trading some well-known theoretical and computational difficulties to an *a posteriori* estimation of risk and reliability. Every practical optimization problem can be unscented; hence, the concepts introduced in this paper can be applied to a wide range of problems in astrodynamics. If unscented optimization techniques are used during the early phases of a mission design, it holds the potential to provide program managers quick estimates on risk, reliability and associated costs so that "optimal missions" do not suffer from cost overruns due to requirements creep. Using numerical examples, we demonstrate how it is possible to reduce risk from 50% all the way down to 1%.

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AAS 15-609

HIGH-FIDELITY LOW-THRUST SEP TRAJECTORIES FROM EARTH TO JUPITER CAPTURE

Sean Patrick[*] and Alfred E. Lynam[†]

Triple Satellite aided capture sequences use gravity-assists at three of Jupiter's four massive Galilean moons to capture into Jupiter orbit. In this paper, three solar electric propulsion (SEP), low-thrust trajectories from Earth to Jupiter capture are optimized using JPL's high-fidelity Mystic software. A Mars gravity assist is used to augment the heliocentric trajectories. Gravity assist flybys of Callisto, Ganymede, and Io or Europa are used to capture into Jupiter Orbit. With between 89.8 and 137.2-day periods, the orbits are shorter than most capture orbits. Thus, the main satellite tour of the Jupiter mission could begin sooner using this strategy.

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LISSAJOUS ORBIT CONTROL FOR THE DEEP SPACE CLIMATE OBSERVATORY SUN-EARTH L1 LIBRATION POINT MISSION

Craig E. Roberts,[*] Sara Case[†] and John Reagoso[‡]

On June 7, 2015, the Deep Space Climate Observatory mission—launched February 11, 2015—became the first National Oceanic and Atmospheric Administration spacecraft to be placed in orbit about the Sun-Earth L1 collinear point, a location ideal for its dual solar weather measurement and Earth full-disk imaging programs. In addition to orbital stationkeeping maneuvers, long-term control of the Lissajous orbit is necessary so that it avoids a Solar Exclusion Zone (SEZ) of four degrees about the Sun, is required. The 'Z-axis control' technique consists of maneuvers to freeze the Lissajous phase such that the same avoidance pattern is repeated continually. Maneuver strategy for both stationkeeping and SEZ avoidance are described. Stationkeeping techniques similar to those used for past and current libration point missions will be adapted to use for DSCOVR. Similarly, an adaptation of the successful SEZ avoidance technique first used in controlling the Lissajous orbit of the Advanced Composition Explorer mission from 1999 to 2001 will also be used for DSCOVR.

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AAS 15-613

EARLY MISSION MANEUVER OPERATIONS FOR THE DEEP SPACE CLIMATE OBSERVATORY SUN-EARTH L1 LIBRATION POINT MISSION

Craig E. Roberts,[*] Sara Case,[†] John Reagoso[‡] and Cassandra Webster[§]

The Deep Space Climate Observatory mission launched on February 11, 2015, and inserted onto a transfer trajectory toward a Lissajous orbit around the Sun-Earth L1 libration point. This paper presents an overview of the baseline transfer orbit and early mission maneuver operations leading up to the start of nominal science orbit operations. In particular, the analysis and performance of the spacecraft insertion, mid-course correction maneuvers, and the deep-space Lissajous orbit insertion maneuvers are discussed, comparing the baseline orbit with actual mission results and highlighting mission and operations constraints.

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RAPID GENERATION OF OPTIMAL ASTEROID POWERED DESCENT TRAJECTORIES VIA CONVEX OPTIMIZATION

Robin Pinson[*] **and Ping Lu**[†]

This paper investigates a convex optimization based method that can rapidly generate the fuel optimal asteroid powered descent trajectory. The ultimate goal is to autonomously design the optimal powered descent trajectory on-board the spacecraft immediately prior to the descent burn. Compared to a planetary powered landing problem, the major difficulty is the complex gravity field near the surface of an asteroid that cannot be approximated by a constant gravity field. This paper uses relaxation techniques and a successive solution process that seeks the solution to the original nonlinear, nonconvex problem through the solutions to a sequence of convex optimal control problems.

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GUIDANCE AND NAVIGATION OF A CALLISTO-IO-GANYMEDE TRIPLE FLYBY JOVIAN CAPTURE

Alan M. Didion[*] and Alfred E. Lynam[†]

Use of a triple-satellite-aided capture to enter Jovian orbit reduces insertion ΔV and provides close flyby science opportunities at three of Jupiter's four large Galilean moons. This capture can be performed while maintaining appropriate Jupiter standoff distance and setting up a suitable apojove for plotting an ex-tended tour. This paper focuses on the guidance and navigation of such trajectories in the presence of spacecraft state errors, ephemeris errors, and maneuver execution errors. A powered-flyby trajectory correction maneuver (TCM) is added to the nominal trajectory at Callisto and the nominal Jupiter orbit insertion (JOI) maneuver is modified to both complete the capture and target the Ganymede flyby. A third TCM is employed after the flybys to act as a JOI cleanup maneuver. A Monte Carlo simulation shows that the statistical ΔV required to correct the trajectory is quite manageable.

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AAS 15-629

SWITCHING PATHS AT THE LUNAR ‘ROUTER’: FINDING VERY LOW-COST TRANSFERS BETWEEN USEFUL TRAJECTORY SEQUENCES IN THE EARTH-MOON SYSTEM[*]

Timothy P. McElrath[†] and Rodney L. Anderson[‡]

The Earth-Moon system allows many types of transfers between lunar encounters, including orbits with low perigees. Combinations of transfers can produce several different useful ballistic trajectory sequences. With the right orbit types (particularly backflips) included, a low thrust vehicle can cheaply switch between sequences that have very different characteristics. Several useful repeat sequences are presented in the circular restricted 3-body problem (CR3BP) model, and examples of these are demonstrated in the full ephemeris. These trajectory sequences would be particularly applicable for returned asteroids (in the near term) and lunar-derived resource transport (in the long term), where only very limited delta-V is available due to the large mass of the vehicle.

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NODE PLACEMENT CAPABILITY FOR SPACECRAFT TRAJECTORY TARGETING IN AN EPHEMERIS MODEL

Christopher Spreen,[*] Kathleen Howell[†] and Belinda Marchand[‡]

Targeting and guidance are nontrivial processes that require experience and system knowledge to implement efficiently. Additional complexities arise when these processes are implemented within a non-Keplerian dynamical environment. In such applications, results are usually obtained by employing a discretized representation of the trajectory in terms of a series of nodes or patch points, each reflecting the full state of the vehicle along its trajectory at a specific time. The objective of this investigation is the development of an interactive, as well as, an automated process, in an ephemeris model, through which nodes are modified in the numerical algorithm by leveraging stability information to support trajectory modification. Through these processes, solutions in complex regimes are constructed to enable successful operations. A hybrid differential corrections algorithm that combines strengths from several previous algorithms is also presented.

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AAS 15-641

CREATING AN END-TO-END SIMULATION FOR THE MULTI-PURPOSE CREWED VEHICLE AND SPACE LAUNCH SYSTEM

Daniel K. Litton,[*] Rafael A. Lugo,[†] Min Qu,[‡] Anthony S. Craig,[§]
Jeremy D. Shidner,[†] Badejo O. Adebonojo, Jr.,[**]
Richard G. Winski[†] and Richard W. Powell[†]

The NASA Engineering & Safety Center (NESC) has commissioned a study to determine the benefits of combining the Space Launch System (SLS) high fidelity trajectory simulations for ascent, the Multi-Purpose Crew Vehicle's (MPCV) simulations for on-orbit operations, and Earth re-entry simulation using a Multidisciplinary Design Optimization (MDO) approach. A commercially available program, Isight, has been selected to combine and optimize all the facets for the Exploration Mission 1 (EM-1). This seamless integration of all the aspects will enable Mission Planners to directly determine the interactions between all phases of the mission. Mission Planners will have more insight in determining overall mission feasibility, margins, and vehicle sizing. The end-to-end integration enables investigation of mission design parameters such as only launching during the day. The ability to easily modify parameters such as launch time and main engine cut-off (MECO) targets not only help determine mission feasibility but also facilitate saving on operation and mission design costs.

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AAS 15-644

PLANAR OPTIMAL TWO-IMPULSE TRANSFERS

Thomas Carter[*] **and Mayer Humi**[†]

The problem of finding a planar two-impulse transfer orbit between two known Keplerian orbits that minimizes the total characteristic velocity of the transfer arc is examined. Using a transformation of the variables presented in previous work, necessary conditions for an optimal transfer are determined, followed by a proof that an optimal transfer exists, concluding with some sufficiency arguments.

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AAS 15-645

PLANAR OPTIMAL TWO-IMPULSE CLOSED-FORM SOLUTIONS OF TRANSVERSE TRANSFERS

Thomas Carter[*] **and Mayer Humi**[†]

The problem of finding a planar two-impulse transfer orbit between two known Keplerian orbits that minimizes the total characteristic velocity of the transfer arc is examined.

Closed-form minimizing solutions are found for all cases in which elliptical boundary orbits are coaxial and all cases in which apses of boundary elliptical orbits are equidistant from the center of attraction. For these cases the minimizing transfers are transverse, and the transfer orbits are tangent to the boundary orbits at apses.

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AAS 15-647

OPTIMAL ENERGY MANAGEMENT STEERING FOR LAMBERT'S PROBLEM USING HYBRID OPTIMIZATION METHOD

Sihang Zhang,[*] Hongguang Yang[†] and Chao Han[‡]

For Lambert's problem, the optimal energy management steering method and the general optimal energy management steering method have been proposed and utilized to minimize the maneuver of the thruster during the burn. In comparison with existing method, the optimal energy management steering, with smaller maneuver angle of the thruster, is smoother and more accurate. A hybrid optimization method is implemented for the optimal steering solution whereby the costates are added to the vector of free parameters and the performance index is directly minimized. Numerical results are presented to demonstrate the efficiency, accuracy and stability of the method.

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AAS 15-658

TRAJECTORY DESIGN OF THE TIME CAPSULE TO MARS STUDENT MISSION

Jonathan D. Aziz,*[*] Sean Napier,[†] Stijn De Smet[†] and Jeffrey S. Parker[‡]

Time Capsule to Mars (TC2M) is a student-led mission with collaboration across universities guided by industry volunteers that will deliver a time capsule containing digital text, images, audio and video to Mars. TC2M intends to demonstrate the capability of CubeSats for interplanetary travel while leveraging new CubeSat subsystem technologies. This work highlights the TC2M trajectory design and optimization. A study of the tradespace, namely mission event dates, fuel requirements and arrival conditions, is presented for a target launch in 2018. An ion Electrospray Propulsion System for CubeSats allows TC2M to escape Earth orbit and intercept Mars with minimum-time trajectories computed to be under 214 days. For minimum-fuel optimization, just 1.867 kg propellant of an 8.0 kg wet mass is required but at a longer 296 days time of flight. A nominal trajectory is selected to illustrate the Earth-escape spiral and interplanetary transit that can guide TC2M towards direct entry into the Martian atmosphere. Investigation of missed-thrust events along the nominal trajectory shows that carrying an excess 10% propellant mass is sufficient for mission success.

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AAS 15-662

COMBINING SIMULATION TOOLS FOR END-TO-END TRAJECTORY OPTIMIZATION

Ryan Whitley,[*] Jeffrey Gutkowski,[†] Scott Craig,[‡] Tim Dawn,[‡]
Jacob Williams,[§] Cesar Ocampo,[**] William B. Stein,[††]
Daniel Litton,[‡‡] Rafael Lugo[§§] and Min Qu[‡‡]

Trajectory simulations with advanced optimization algorithms are invaluable tools in the process of designing spacecraft. Due to the need for complex models, simulations are often highly tailored to the needs of the particular program or mission. NASA's Orion and SLS programs are no exception. While independent analyses are valuable to assess individual spacecraft capabilities, a complete end-to-end trajectory from launch to splashdown maximizes potential performance and ensures a continuous solution. In order to obtain end-to-end capability, Orion's in-space tool (Copernicus) was made to interface directly with the SLS's ascent tool (POST2) and a new tool to optimize the full problem by operating both simulations simultaneously was born.

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AAS 15-664

MULTI-OBJECTIVE SEARCH FOR MULTIPLE GRAVITY ASSIST TRAJECTORIES

Demyan Lantukh[*] and Ryan P. Russell[†]

A systematic multiple gravity assist grid search and multi-level pruning algorithm is presented. *Explore*, a trajectory pathsolving tool, implements this parallelizable, breadth-first algorithm. Decomposing the problem into a sequence of subproblems enables the inclusion of different trajectory segment and patching condition types. Comparisons between performing the search with ballistic transfers, impulsive maneuvers, and low-thrust approximation are presented. Pruning is conducted using constraints and multi-objective Pareto ranking with performance indices. The solution storage structure allows solution space subdivision and reduces data duplication. Detailed review of multiple gravity assist trajectory search methods and software provides context for the presented method.

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AAS 15-668

EVOLUTIONARY OPTIMIZATION OF A RENDEZVOUS TRAJECTORY FOR A SATELLITE FORMATION WITH A SPACE DEBRIS HAZARD

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

Orbital debris continues to pose a serious threat to space assets in low Earth orbit (LEO). In response, active debris mitigation approaches have been proposed – including the coordinated activities of satellite formations. A critical first step is the determination of the optimal trajectory for the satellite formation to rendezvous with the debris subject to prescribed mission constraints. Motivated by this scenario, differential evolution is used to optimize multi-satellite rendezvous trajectory problems with topological constraints. Initial impulsive maneuvers are sought for groups of $N = 4; 5$ satellites that lead to debris rendezvous in the form of a planar square and trigonal bipyramid, respectively.

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AAS 15-682

FUEL-EFFICIENT PLANETARY LANDING GUIDANCE WITH HAZARD AVOIDANCE

Yanning Guo,[*] Hutao Cui,[†] Yao Zhang[‡] and Guangfu Ma[§]

Two improved zero-effort-miss (ZEM) and zero-effort-velocity (ZEV) optimal guidance laws are proposed in this paper based on the classical optimal feedback guidance theory in order to avoid obstacles as well as precision landing. The velocity of the vehicle is brought into the performance index, which will ensure the vehicle never crash the obstacles, especially when the vehicle is close to an obstacle, the big value velocity can help the vehicle avoid it. Furthermore, two new avoidance strategies are put forward to make the landing process more reasonable, which rely on not only the experience but also the motion state of the vehicle. Finally, simulation results show the effectiveness of the methods proposed in this paper.

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AAS 15-693

SIMPLE GRAVITATIONAL MODELS AND CONTROL LAWS FOR AUTONOMOUS OPERATIONS IN PROXIMITY OF UNIFORMLY ROTATING ASTEROIDS

Andrea Turconi,[*] Phil Palmer[†] and Mark Roberts[‡]

Maintaining missions in proximity of small bodies requires extensive orbit determination and ground station time due to a ground-in-the-loop approach. Recent developments in on-board navigation paved the way for autonomous proximity operations. The missing elements for achieving this goal are a gravity model, simple enough to be easily used by the spacecraft to steer itself around the asteroid, and guidance laws that can make use of such inherently simple model. In this paper we derive a simple three point mass model and propose control laws that can take advantage of the characteristics of this approximate model.

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AAS 15-694

ASTEROID IMPACT MISSION: A POSSIBLE APPROACH TO DESIGN EFFECTIVE CLOSE PROXIMITY OPERATIONS TO RELEASE MASCOT-2 LANDER

Fabio Ferrari* **and Michèle Lavagna†**

The paper presents the design of the landing strategy, during close proximity operations of ESA's Asteroid Impact Mission. The target of the mission is the binary asteroid system 65803 Didymos and the objective of this work is to investigate design opportunities to land a small and passive probe on the smaller asteroid of the couple. The dynamics of the spacecraft in the proximity of the binary system is naturally modeled using a three-body problem formulation. The landing requirements are highlighted and a suitable strategy is selected, by conveniently exploiting three-body dynamics. Uncertainties in release and touch down conditions are modeled to guarantee the robustness of the chosen solution to achieve successful landing.

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AAS 15-701

EXPLOITING SYMMETRY IN HIGH ORDER TENSOR-BASED SERIES EXPANSION ALGORITHMS

Mohammad Alhulayil,[*] Ahmad Bani Younes[†] and James Daniel Turner[‡]

Many applications in science and engineering require the calculations of partial derivative models. Computational differentiation has been developed as a software technology for addressing this need. General numerical models are available for generating first-fourth order sensitivity models. The challenge addressed in this work is concerned with efficiently generating and storing the tensor-based calculations. Sensitivity calculations are of interest for both initial conditions and parameters. A major challenge encountered in high dimensioned real-world applications, is that both the computations and data storage requirements scale nonlinearly. This work addresses the problem of exploiting the tensor symmetry arising in the generation, storage, and computation using symmetrized models for hessian and higher order sensitivity tensors. Extensive modifications are required for operator-overloaded derivative tools for exploiting the symmetrized tensor models. Typical applications include problems in applied mathematics, probability theory, optimization, control theory, and computer science. Several applications are presented to demonstrate the significant impact on both memory allocations and symmetric-based computational algorithms.

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AAS 15-702

EXPLOITING SPARSITY IN TENSOR-BASED COMPUTATIONAL DIFFERENTIATION ALGORITHMS

Mohammad Alhulayil,[*] Ahmad Bani Younes[†] and James Daniel Turner[‡]

High order tensor models for applications in science and engineering require the calculation of partial derivative models. It is well known that Jacobian sensitivity problems have sparse structures, for which many powerful and effective algorithms have been developed. This paper explores to extension of these sparse technologies for higher-order gradient calculations. All partial derivatives are generated by using Computational differentiation software. Two levels of sparsity are explored. First, known structural sparsity arising from the transformation of 2nd order differential equation models into state space form, where the resulting Jacobian structure easily exploited. Second, application-specific sparsity, where sensitivity calculations produce zero results for all derivative orders. Two issues are important for exploitation: first, the known zero sub-blocks of the gradient tensor are replicated in the higher order tensors, which provides a significant boost in derivative calculation performance; and second, both memory usage and numerical computation are restructured. Numerical examples are presented using the classical two-body problem, where it is shown the performance boost for the known Jacobean structure is 38X for a fourth-order approximation.

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AAS 15-706

FAST SEARCH ALGORITHM OF HIGH-PRECISION EARTH-MOON FREE-RETURN TRAJECTORY

**Kun Peng,[*] Shingyik Yim,[†] Bainan Zhang,[‡] Lei Yang,[‡] Linli Guo,[‡]
Yanlong Bu[§] and Sihang Zhang[**]**

Free-return trajectory design is an important guarantee for the safety of manned lunar mission. This trajectory can ensure that the spacecraft returns to Earth without any maneuver when the mission goes wrong. A fast search algorithm of high-precision Earth-Moon free-return trajectory is proposed in this paper. It is consisted of four parts: 1) solution model establishment for high-precision free-return trajectory, 2) initial values estimation for control variables, 3) multilevel search for free-return trajectory, 4) extended search for multiple types of free-return trajectory. This algorithm can search the accurate free-return trajectory without any designer-provided prior information, and can converge rapidly.

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SOLAR SAIL TRANSFERS FROM EARTH TO THE LUNAR VICINITY IN THE CIRCULAR RESTRICTED PROBLEM

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

The lunar region enables a variety of mission scenarios that advance space exploration. However, a return to this region of space implies the development of alternative strategies to support affordable mission design options subject to limited resource utilization. Hence, a general solar sail framework is developed to probe the capabilities associated with transfer options employing natural pathways. Prior investigations related to Earth-escape strategies, low thrust regimes and the development of desirable destination orbits at/near a primary all contribute. But, realistic mission constraints such as current sail technology levels, sail inefficiencies, occultation events and limitations on sail maneuverability all impact performance.

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AAS 15-724

COMPARISON OF OVERALL PROPULSION SYSTEM EFFECTIVENESS FOR ORBIT INSERTION AND ESCAPE[*]

Nathan Strange[†] and James Longuski[‡]

Although specific impulse is often used as the primary measure of propulsion system efficiency, lower specific impulse systems with a smaller inert masses can often provide better performance than higher specific impulse systems. In addition, chemical propulsion systems can outperform much higher specific impulse electric propulsion systems when they can take advantage of the Oberth effect, i.e. an impulsive maneuver deep in a gravity well. We show that for many cases solid rockets would outperform higher specific impulse liquid systems. We also show that for low v-infinities, chemical systems would outperform electric propulsion systems for orbit insertion and escape maneuvers.

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AAS 15-728

LOW-THRUST EARTH-ORBIT TRANSFER OPTIMIZATION USING ANALYTICAL AVERAGING WITHIN A SEQUENTIAL METHOD

David Morante,[*] Manuel Sanjurjo[†] and Manuel Soler[†]

A robust and flexible algorithm for computing optimal low-thrust Earth orbit transfer is proposed. This approach is based on three sequential steps of growing complexity. Each of the steps is grounded on methods developed in the literature and attempts to obtain near-optimal solutions in an effective manner. They will be reviewed independently comparing their own partial outcome, advantages and disadvantages. At the first and second steps, analytical averaging is used to propagate efficiently the trajectory together with predefined control laws. Finally, based on the previous near-optimal solutions, the optimal control problem will be addressed via a Direct Collocation Method.

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AAS 15-729

GENERALIZED LOGARITHMIC SPIRALS FOR LOW-THRUST TRAJECTORY DESIGN

Javier Roa[*] and Jesús Peláez[†]

Shape-based approaches are practical for finding sub-optimal solutions during the preliminary design of low-thrust trajectories. Logarithmic spirals are the simplest, but of little practical interest due to having a constant flight-path angle. We prove that the same tangential thrust profile that generates a logarithmic spiral yields an entire family of generalized spirals. The system admits two integrals of motion, which are equivalent to the energy and the angular momentum equations. Three different subfamilies of spiral trajectories are obtained depending on the sign of the constant of the generalized energy: elliptic, parabolic, and hyperbolic. Parabolic spirals are equivalent to logarithmic spirals. Elliptic spirals are bounded; never escape to infinity and the trajectory is symmetric. Two types of hyperbolic spirals have been found: the first has only one asymptote; the second has two asymptotes, the trajectory is symmetric and never falls to the origin. The solution is obtained when solving rigorously the equations of motion with no prior assumptions. Closed-form expressions for both the trajectory and the time of flight are provided.

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AAS 15-756

MISSION DESIGN ANALYSIS FOR THE MARTIAN MOON PHOBOS: CLOSE FLYBYS, MISSED THRUSTS, AND OTHER IN-FLIGHT ENTERTAINMENT[*]

Jeffrey Stuart,[†] Tim McElrath[‡] and Anastassios Petropoulos[§]

A robotic mission to the Martian moons Phobos and Deimos would offer a wealth of scientific information and serve as a useful precursor to potential human missions. In this paper, we investigate a prospective mission enabled by solar electric propulsion that would explore Phobos via a series of flybys followed by capture into orbit around the moon. Of particular interest are low ΔV options for capture and walkdown to the target science orbits aided by multi-body effects due to the mutual gravitational interaction of Phobos and Mars. We also consider contingency operations in the event of missed thrust or maneuver execution errors.

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AAS 15-757

SYSTEMATIC DESIGN OF OPTIMAL LOW-THRUST TRANSFERS FOR THE THREE-BODY PROBLEM

Shankar Kulumani[*] **and Taeyoung Lee**[†]

A computational approach is developed for the design of continuous low thrust transfers in the planar circular restricted three-body problem. The transfer design method of invariant manifolds is extended with the addition of continuous low thrust propulsion. A reachable region is generated and it is used to determine transfer opportunities, analogous to the intersection of invariant manifolds. The reachable set is developed on a lower dimensional Poincaré section and used to design transfer trajectories. This is solved numerically as a discrete optimal control problem using a variational integrator. This provides for a geometrically exact and numerically efficient method for the motion in the three-body problem. A numerical simulation is provided developing a transfer from a L_1 periodic orbit in the Earth-Moon system to a target orbit about the Moon.

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AAS 15-758

TRAJECTORIES FOR A NEAR TERM MISSION TO THE INTERSTELLAR MEDIUM

Nitin Arora,[*] Nathan Strange[†] and Leon Alkalai[‡]

Trajectories for rapid access to the interstellar medium (ISM) with a Kuiper Belt Object (KBO) flyby, launching between 2022 and 2030, are described. An impulsive-patched-conic broad search algorithm combined with a local optimizer is used for the trajectory computations. Two classes of trajectories, (1) with a powered Jupiter flyby and (2) with a perihelion maneuver, are studied and compared. Planetary flybys combined with leveraging maneuvers reduce launch C_3 requirements (by factor of 2 or more) and help satisfy mission-phasing constraints. Low launch C_3 combined with leveraging and a perihelion maneuver is found to be enabling for a near-term mission to the ISM.

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AAS 15-759

FRACTIONATED SATELLITE SYSTEMS FOR EARTH OBSERVATION MISSIONS: FEASIBILITY AND PERFORMANCES ANALYSES

Daniele Filippetto[*] and Michèle Lavagna[†]

This paper aims at investigating the feasibility of fractionated satellite architecture for Earth observation missions. The payload fractionation, consisting in the physical distribution of the payload over a cluster of satellites flying in formation or constellation, can be obtained using either the same or a different payload in each satellite. Issues, possible solutions and applications (visible/infrared and synthetic aperture radar remote sensing) of both of these approaches are analysed in this study. In particular, the problems of deployment, configuration maintenance and reconfiguration are addressed with formation examples in different orbits. The results are critically discussed in the paper.

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AAS 15-766

OPTIMAL LOW-THRUST GEOSTATIONARY TRANSFER ORBIT USING LEGENDRE-GAUSS-RADAU COLLOCATION

Andrew M. S. Goodyear[*] and David B. Spencer[†]

A reformulation of Edelbaum's equations for low thrust orbit raising between two circular orbits with an inclination change using optimal control theory was performed. A nonsingular modified equinoctial element set was used, and higher order gravitational harmonics up to and including J_5 were included within the model. An indirect optimization scheme was performed to obtain an optimal pitch steering law, and the state and costate equations were solved using a Legendre-Gauss-Radau collocation scheme. The numerical solution was broken up into two phases. The first phase has the objective of raising an orbit into a zone in which eclipsing is no longer an issue, and the second phase involves solving a two-point boundary value problem in order to finish the maneuver.

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AAS 15-775

PROGRADE LUNAR FLYBY TRAJECTORIES FROM DISTANT RETROGRADE ORBITS

Kathryn E. Davis[*] **and Jeffrey S. Parker**[†]

This paper examines trajectories from Distant Retrograde Orbits (DROs) that perform prograde lunar flybys. Small perturbations are applied to nominal states on DROs and propagated forward in time. Perturbations as low as 20 m/s can initiate prograde lunar flybys and 13% of all nominal DRO states perturbed by 100 m/s will result in a prograde lunar flyby. Topologically similar trajectories have correlated perturbation directions. Prograde flybys from a given DRO are used as initial guesses to locate additional prograde flybys from DROs of varying amplitudes. The results presented here may aid in designing low-cost transfers between DROs and other orbits.

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AAS 15-783

PIECE-WISE CONSTANT CHARGING STRATEGY FOR THE RECONFIGURATION OF A 3-CRAFT COULOMB FORMATION

Yinan Xu[*] and Shuquan Wang[†]

This paper investigates the non-equilibrium fixed-shape three-craft Coulomb formation reconfiguration problem. Being aware of that using feedback control approach results in the chattering of the charges due to the non-equilibrium nature of the system dynamics, this paper proposes a trajectory program approach to accomplish the reconfiguration. The entire maneuver trajectories are divided into multiple phases. During each phase, only two of the three craft are charged. In this way the relative trajectory of the charged spacecraft during a certain phase is a conic section. The entire trajectories are composed of patched conics and/or straight lines. The procedures determining the three-phase maneuver strategy is developed, including a preadjusting phase and two transition phases. Numerical simulations demonstrate the effectiveness of the algorithm and the elegance of the control charges.

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AAS 15-785

ON THE ACCURACY OF TRAJECTORY STATE TRANSITION MATRICES

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

Accurate partial derivatives are of the utmost importance for optimization and root-solving algorithms, but can prove challenging and computationally expensive to obtain. Modern space missions often require highly sensitive trajectories, increasing the need for accurate partials. Different techniques for computing state-transition matrices for trajectory optimization are analyzed, in particular for low-fidelity propagations. Analytical methods are compared to the complex step derivative approximation and finite differences methods, for a variety of problems and integration techniques. The subtle differences between variable- and fixed-step integration for partial computation are revealed, common pitfalls are observed, and recommendations are made to enhance the quality of state transition matrices. A main result is the demonstration of small but potentially significant errors in the partials when they are computed with variational equations and a variable-step integrator.

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AAS 15-794

CIRCUMLUNAR FREE-RETURN CYCLER ORBITS FOR A MANNED EARTH-MOON SPACE STATION

Anthony L. Genova[*] and Buzz Aldrin[†]

Multiple free-return circumlunar cycler orbits were designed to allow regular travel between the Earth and Moon by a manned space station. The presented cycler orbits contain circumlunar free-return “figure-8” segments and yield lunar encounters every month. Smaller space “taxi” vehicles can rendezvous with (and depart from) the cycling Earth-Moon space station to enter lunar orbit (and/or land on the lunar surface), return to Earth, or reach destinations including Earth-Moon halo orbits, near-Earth objects (NEOs), and Mars. To assess the practicality of the selected orbits, relevant cycler characteristics (including ΔV maintenance requirements) are presented and compared.

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AAS 15-812

CONJUGATE UNSCENTED TRANSFORMATION BASED COLLOCATION SCHEME TO SOLVE THE HAMILTON JACOBI BELLMAN EQUATION

Nagavenkat Adurthi,[*] Puneet Singla[†] and Manoranjan Majji[‡]

This paper deals with the development of a computational efficient approach to approximate the solution to the Hamilton Jacobi Bellman equation. The primary focus is to generate optimal feedback controllers for nonlinear systems in higher dimensions. Solving the Hamilton Jacobi Bellman partial differential equation is known to be a computationally challenging problem due to the curse of dimensionality with the increase in dimension. A collocation based approach is adopted, where the collocation points are chosen as the recently developed Conjugate Unscented Transform points to avoid the curse of dimensionality. Further a l_1-norm based optimization problem is proposed to optimally select the basis that is suitable for the given dynamical system.

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AAS 15-817

PIECEWISE INITIAL LOW THRUST TRAJECTORY DESIGN

Ossama Abdelkhalik[*] and Shadi Ahmadi Darani[†]

In this paper the problem of preliminary trajectory design is considered for a transfer from a low Earth orbit to a geostationary orbit using low thrust acceleration, assuming no thrust during eclipse periods. This problem is challenging for many preliminary trajectory design tools due to the very high number of revolutions around Earth and the very low thrust level constraint. The approach presented in this paper assumes a profile for the desired change in each of the orbit parameters and implements a feedback control to track this profile. In the case when the trajectory is near circular, a linear dynamic model can be used in designing the controller gains. In this paper, two dynamic models, linear and nonlinear, are considered and a different controller is designed for each model. By dividing the trajectory into small segments, a piecewise orbit change is achieved in both cases. The controller gains are tuned at each segment. Case studies are presented.

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SPACE MISSIONS: NEW HORIZONS, MESSENGER, AND MARS RECONNAISSANCE ORBITER

Session Chairs:

Bobby Williams, KinetX Inc.

James McAdams,
The Johns Hopkins University Applied Physics Laboratory

The following paper was not available for publication:

AAS 15-651 Paper Withdrawn

AAS 15-532

MARS RECONNAISSANCE ORBITER NAVIGATION STRATEGY FOR DUAL SUPPORT OF INSIGHT AND EXOMARS ENTRY, DESCENT AND LANDING DEMONSTRATOR MODULE IN 2016[*]

Sean V. Wagner,[†] Premkumar R. Menon,[‡]
Min-Kun J. Chung[§] and Jessica L. Williams[**]

Mars Reconnaissance Orbiter (MRO) will support NASA's InSight Mission and ESA's ExoMars Entry, Descent and Landing Demonstrator Module (EDM) in the fall of 2016 when both landers arrive at Mars. MRO provided relay support during the Entry, Descent and Landing (EDL) sequences of the Mars Phoenix Lander in May 2008 and the Mars Science Laboratory in August 2012. Unlike these missions, MRO will coordinate between two EDL events separated by only three weeks: InSight on September 28, 2016 and EDM on October 19, 2016. This paper describes the MRO Navigation Team's maneuver strategy to move the spacecraft's ascending node for InSight EDL support and to adjust the orbit timing (phasing) to meet InSight and EDM phasing requirements.

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AAS 15-551

MARS RECONNAISSANCE ORBITER NAVIGATION STRATEGY FOR THE COMET SIDING SPRING ENCOUNTER[*]

**Premkumar R. Menon,[†] Sean V. Wagner, Tomas J. Martin-Mur,
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Kyong J. Lee and William B. Schulze[‡]**

Comet Siding Spring encountered Mars on October 19, 2014 at a distance of about 140,500 km – the nearest comet flyby of a planet in recorded history. Mars Reconnaissance Orbiter (MRO) was able to detect the comet, gather science data, and capture images of the comet as it approached Mars. To help protect MRO from the incoming comet particles, two propulsive maneuvers were performed to position the spacecraft behind Mars at the arrival time of the expected peak particle fluency. This paper documents the strategy that the MRO Navigation Team executed to mitigate risk from the comet particles while allowing scientific observations of the comet flyby.

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AAS 15-608

DESIGN, IMPLEMENTATION, AND OUTCOME OF MESSENGER'S TRAJECTORY FROM LAUNCH TO MERCURY IMPACT

Dawn P. Moessner[*] **and James V. McAdams**[†]

MESSENGER launched on 3 August 2004, entered orbit about Mercury on 18 March 2011 (UTC), and impacted Mercury's surface on 30 April 2015. After a 6.6-year cruise phase with one flyby of Earth, two of Venus, and three of Mercury, MESSENGER spent 4.1 years in orbit about the innermost planet. Initially in a 12-h orbit, MESSENGER maintained periapsis altitudes of 200–505 km before transferring to an 8-h orbit on 20 April 2012. MESSENGER's low-altitude campaign included periapsis altitudes between 15 and 200 km. In its final 44 days, MESSENGER maintained unprecedented minimum altitudes less than 38 km above Mercury's terrain before impact.

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AAS 15-634

ENGINEERING MESSENGER'S GRAND FINALE AT MERCURY – THE LOW-ALTITUDE HOVER CAMPAIGN

**James V. McAdams,[*] Christopher G. Bryan,[†] Stewart S. Bushman,[‡]
Andrew B. Calloway,[§] Eric Carranza,[**] Sarah H. Flanigan,[††]
Madeline N. Kirk,[‡‡] Haje Korth,[§§] Dawn P. Moessner,[***]
Daniel J. O'Shaughnessy[†††] and Kenneth E. Williams[‡‡‡]**

Having completed its primary and first extended missions by mid-March 2013, the MESSENGER spacecraft in orbit about Mercury began a 2.1-year final mission extension that brought substantial opportunity for low-altitude science, along with many technical challenges successfully overcome by the flight operations and science teams. After four orbit-correction maneuvers (OCMs) between June 2014 and January 2015 targeted minimum altitudes near 25 km and 15 km, seven OCMs in March and April 2015 maintained minimum altitude between 5 km and 37 km. Engineering challenges at mission end included the efficient utilization of accessible propellant and helium gas pressurant to delay Mercury impact.

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AAS 15-636

NAVIGATION STRATEGY AND RESULTS FOR NEW HORIZONS' APPROACH AND FLYBY OF THE PLUTO SYSTEM

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S. A. Stern,[‡] **H. A. Weaver,**[†] **L. A. Young,**[‡] **K. Ennico**[§] and **C. B. Olkin**[‡]

The New Horizons mission, the first mission in NASA's New Frontiers Program, is also the first mission with primary science objectives to explore the Pluto/Charon system. After launch in January 2006 and an interplanetary cruise of more than 9.5 years, New Horizons has completed the approach and flyby of Pluto. This paper presents an overview of the analysis and operational constraints that led to the navigation strategy used. Also presented are operational results for that strategy during this final phase of the prime mission.

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AAS 15-652

MESSENGER MANEUVER PERFORMANCE DURING THE LOW-ALTITUDE HOVER CAMPAIGN

**Madeline N. Kirk,[*] Sarah H. Flanigan,[†] Daniel J. O'Shaughnessy,[‡]
Stewart S. Bushman[§] and Paul E. Rosendall[**]**

Helium gas pressurant from the MErcury Surface, Space ENvironment, GEochemistry, and Ranging (MESSENGER) spacecraft's near-empty main fuel tanks was used as a propellant to delay the spacecraft's surface impact onto Mercury until late April 2015 and enabled a one-month "hover" campaign with periapsis altitudes as low as 5 km. The final eight maneuvers of the mission had special challenges, including repurposing helium pressurant as a propellant, firing thrusters that had not been used in more than eight years, and executing multiple maneuvers within a short time frame that, if unsuccessful, would have led to impact times as little as 30 hours later.

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AAS 15-768

NAVIGATION AND DISPERSION ANALYSIS OF THE FIRST ORION EXPLORATION MISSION

Christopher D'Souza[*] and Renato Zanetti[*]

This paper presents the Orion EM-1 Linear Covariance Analysis for the DRO mission. The $|\Delta V|$ statistics for each maneuver are presented. In particular, the statistics of the lunar encounters and the Entry Interface are presented.

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HIGH PERFORMANCE COMPUTING IN ASTRONAUTICS

Session Chairs:

Nitin Arora, Jet Propulsion Laboratory
Sergey Tanygin, Analytical Graphics, Inc.

AAS 15-535

A MASSIVELY PARALLEL BAYESIAN APPROACH TO PLANETARY PROTECTION TRAJECTORY ANALYSIS AND DESIGN[*]

Mark S. Wallace[†]

The NASA Planetary Protection Office has levied a requirement that the upper stage of future planetary launches have a less than 10^{-4} chance of impacting Mars within 50 years after launch. A brute-force approach requires a decade of computer time to demonstrate compliance. By using a Bayesian approach and taking advantage of the demonstrated reliability of the upper stage, the required number of fifty-year propagations can be massively reduced. By spreading the remaining embarrassingly parallel Monte Carlo simulations across multiple computers, compliance can be demonstrated in a reasonable time frame. The method used is described here.

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AAS 15-563

INFRARED-SENSOR MODELING AND GPU SIMULATION OF TERMINAL GUIDANCE FOR ASTEROID INTERCEPT MISSIONS

Joshua Lyzhoft,[*] John Basart[†] and Bong Wie[‡]

This paper describes the IR-sensor modeling and simulation problem of a terminal guidance system for asteroid intercept missions. Precision terminal guidance problem of targeting small asteroids (50 to 100 meters in diameter) is investigated in this paper. Signal-to-noise ratio estimation for visual- and IR-sensors, estimation of their minimum and maximum ranges for target detection, and GPU-accelerated simulation of the IR-based terminal guidance are discussed. Scaled polyhedron models of known objects, such as the Rosetta mission's Comet 67P/C-G, OSIRISREx's Bennu, and asteroid 433 Eros, are utilized in developing a GPU-based simulation tool for the IR-based terminal guidance. A parallelized ray tracing algorithm for simulating realistic surface-to-surface shadowing of a given celestial body is developed. Polyhedron solid-angle approximation is also discussed.

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AAS 15-568

A GPU-ACCELERATED COMPUTATIONAL TOOL FOR ASTEROID DISRUPTION MODELING AND SIMULATION

Ben J. Zimmerman[*] and Bong Wie[†]

This paper presents a two-dimensional hydrodynamic simulation tool for studying the effectiveness of hypervelocity kinetic-energy impactors (KEIs) and nuclear subsurface explosions for disrupting (i.e., dispersively pulverizing) hazardous asteroids. High-order methods on GPUs (Graphics Processing Units) are employed for hydrodynamic simulations of such complex physical problems. Because high-order method schemes are compact (many operations per element), they are highly parallelized and are ideal for the architecture of GPUs. This paper focuses on the implementation of such numerical methods with GPUs as applied to the asteroid disruption problem. Three cases are compared for disrupting a reference 2D 100-m asteroid model of a nominal density of 2000 kg/m^3. They are: i) a single, 5000-kg KEI with 10-km/s impact speed, ii) five 1000-kg KEIs in parallel, and iii) a 100-kt nuclear subsurface explosion subsequent to a smaller 500-kg KEI.

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AAS 15-587

PARAMAT: PARALLEL PROCESSING WITH THE GENERAL MISSION ANALYSIS TOOL

Darrel J. Conway[*]

In 2014, Thinking Systems began work on a threaded, parallel processing tool that incorporates the numerical engine from the General Mission Analysis Tool (GMAT) into a system designed to use the processing capabilities of modern, multi-core computer platforms. The goal of this work is to build a modern, parallel processing mission analysis tool designed to solve computationally intensive analysis problems. Examples of the problems targeted by this work are Monte Carlo analysis of spacecraft mission parameters, parametric studies of mission design problems, trajectory dispersion analyses, and phase space analysis of flight mechanics problems. The tool under development, Paramat, currently exists as a proof of concept prototype system. This implementation has been used to show core GMAT functionality driving Monte Carlo analyses for orbital transfers. In this paper, the Paramat system is described, beginning with a design overview and current feature set of the system, followed by walking through a sample analysis problem that demonstrates the performance gains observed in Paramat runs.

GMAT is an open source tool under development at NASA's Goddard Space Flight Center (GSFC). Thinking Systems has been an active participant in GMAT development since the project began in 2002. The GMAT system architecture was proposed based on design work at Thinking Systems, and has been refined throughout the development process to produce a tool which has been released as an open source project. In 2013, GMAT was certified for operational use for maneuver planning by the Advanced Composition Explorer (ACE) mission in the Flight Dynamics Facility at GSFC. Paramat, initially funded through the NASA SBIR/STTR Program, started from a conceptual approach to parallel processing using the GMAT source code. The Paramat system has been built as a proof of concept system designed to fully use the computational resources on an analyst's workstation. Paramat has been used to demonstrate performance gains on Linux, Windows, and Mac workstations when performing analysis that requires repeated runs of a spacecraft mission. Linux is the primary development platform for Paramat, so the results presented here will focus on the system on Linux hardware.

To be a viable system, Paramat must demonstrate the same modeling fidelity as is seen in GMAT. GMAT has a full suite of test scripts that are run on nightly builds of the system. Paramat uses the same scripting language as GMAT, with extensions that support parallel processing problems. Thinking Systems has prototyped a continuous build and test system for Paramat. The Paramat test system, once complete, will exercise the same set of tests as are run for GMAT, generating results for more than 12000 test cases on each run.

Examples of the performance gains seen in the Paramat system are documented in this paper. The primary demonstration mission for this analysis is the Monte Carlo analysis of an orbital transfer problem that GMAT includes as a sample problem in the public releases of the software. Paramat shows performance gains that scale linearly with the hardware capabilities of the workstation running the tool, as will be shown in the data presented here.

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AAS 15-688

GPU-ACCELERATED COMPUTATION OF SRP FORCES WITH GRAPHICAL ENCODING OF SURFACE NORMALS

Sergei Tanygin[*] and Gregory M. Beatty[†]

The forces and torques due to atmospheric drag and solar radiation pressure (SRP) acting on complex and articulated space objects are efficiently calculated by utilizing the highly parallelized hardware available in commodity desktop PC graphics processing units. The calculations are performed by combining traditional OpenGL rendering of 3D models with general-purpose computing on graphics processing units (GPGPU) techniques via OpenCL. In cases when the forces and torques include contributions that depend on surface normals, their directions are encoded as pseudo-colors which allows OpenCL kernel methods to efficiently unpack this additional information and perform the necessary computations. By utilizing the highly parallelized processing units available in commodity GPUs, the time required run the calculations is significantly reduced.

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AAS 15-735

GPU-BASED UNCUED SURVEILLANCE FROM LEO TO GEO WITH SMALL OPTICAL TELESCOPES

Peter Zimmer,[*] John T. McGraw[†] and Mark R. Ackermann[‡]

J.T. McGraw and Associates, LLC (JTMA) operates two proof-of-concept wide-field imaging systems to test novel techniques for uncued surveillance of LEO/MEO/GEO/HEO and, in collaboration with the University of New Mexico (UNM), uses a third small telescope for rapidly queued same-pass follow-up observations. Using our GPU-accelerated detection methods, the proof-of-concept systems operating at sites near and within Albuquerque, NM, have detected objects fainter than V=13 at greater than 6 sigma significance moving at apparent rates in excess of 0.75 degrees per second. Dozens of objects are measured during each operational twilight period, many of which have no corresponding catalog object.

The two proof-of-concept systems, separated by 27 km, work together by taking simultaneous images of a common volume to constrain the orbits of detected objects using parallax measurements. These detections are followed-up by imaging photometric observations taken at UNM to confirm and further constrain the initial orbit determination and independently assess the objects and verify the quality of the derived orbits. This work continues to demonstrate that scalable optical systems designed for real-time detection of fast moving objects, which can be then handed off to other instruments capable of tracking and characterizing them, can provide valuable real-time surveillance data at LEO and beyond, which substantively informs the SSA process.

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AAS 15-791

PARALLEL GENERATION OF EXTREMAL FIELD MAPS FOR OPTIMAL MULTI-REVOLUTION CONTINUOUS THRUST ORBIT TRANSFERS

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

We simulate hybrid thrust transfers to rendezvous with space debris in orbit about the Earth. The hybrid thrust transfer consists of a two-impulse maneuver at the terminal boundaries, which is augmented with continuous low-thrust that is sustained for the duration of the flight. This optimal control problem is formulated using the path approximation numerical integration method, *Modified Chebyshev Picard Iteration* (MCPI). This integration method can be formulated for solving initial and boundary value problems. The boundary value problem formulation does not require a shooting method and converges over about 1/3 of an orbit. This interval can be extended to about 95% of an orbit with regularization. In order to increase this domain even further, to multiple revolution capability, we implement a shooting method known as the *Method of Particular Solutions* (MPS), and utilize the MCPI initial value problem implementation for integrating the state and costate equations. The *p*-iteration Keplerian Lambert solver is used to provide an initial guess for solving the optimal control problem. When continuous thrust is "turned off", we find that the solution to the optimal control formulation reduces to the two-impulse two-point boundary value problem, with zero thrust coast. For some transfers we observe a reduced terminal ΔV cost for the hybrid thrust relative to the two-impulse, and for others it may be increased. This depends on the relative orbits and the initial phasing of the satellites. Determining the globally optimal sequence of maneuvers for retrieving orbital debris can require simulating thousands of feasible transfer trajectories. We utilize a parallel architecture on our cluster at the LASR Lab (Texas A&M), for computing the ΔV cost for each transfer trajectory, and display the results on an extremal field map. Both MCPI and MPS afford several layers of parallelization, and taking advantage of this reduces the computation time by at least an order of magnitude compared with the serial implementation.

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AAS 15-793

MASSIVELY PARALLEL IMPLEMENTATION OF MODIFIED CHEBYSHEV PICARD ITERATION FOR PERTURBED ORBIT PROPAGATION

Austin Probe,* Julie L. Read,* Brent Macomber† and John L. Junkins‡

Future Space Situational Awareness (SSA) sensing capabilities will greatly increase the population of trackable space objects, and consequently, the need for accurate and efficient orbital propagation. The serial formulation of Modified Chebyshev Picard Iteration (MCPI) has proven to be an efficient and accurate method for propagating perturbed orbital motion; its performance is comparable to other state-of-practice numerical integrators. However, one significant advantage of MCPI is that it is well suited to parallelization. Initial efforts to implement MCPI using parallel computation have shown additional speedup. This paper details a graphics card based massively parallel implementation of perturbed orbit propagation with MCPI.

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AAS 15-795

EXPERIMENTS WITH JULIA FOR ASTRODYNAMICS APPLICATIONS

Nitin Arora[*] and Anastassios Petropoulos[†]

Julia's potential for solving complex astrodynamics problems is studied. Julia is a high-level, new, dynamic programming language with performance approaching C/Fortran and has features like inbuilt parallelism, variable accuracy, integrated numerical libraries and direct C and Fortran interfaces. Two astrodynamics problems are solved in Julia: 1) Lambert's problem, using the vercosine formulation and 2) trajectory integration. Implemented algorithms are compared with C and Fortran based counterparts on key performance parameters (speed, development effort, etc.). Using Julia for fast and reliable astrodynamics software development is also discussed.

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AAS 15-808

A NON-LINEAR PARALLEL OPTIMIZATION TOOL (NLPAROPT) FOR SOLVING SPACECRAFT TRAJECTORY PROBLEMS

Alexander Ghosh,[*] Ryne Beeson,[†] Laura Richardson,[‡] Donald Ellison,[*]
David Carroll[§] and Victoria Coverstone[**]

Modern spacecraft trajectory mission planning regularly involves Non-Linear Programming (NLP) problem formulations. As the problems being posed become more complex, scientists have adopted high performance computing methods such as parallel programming to significantly speed up the time-to-solution. Unfortunately, the NLP solvers at the core of many of the modern trajectory optimization methods are becoming a serial bottleneck, and the single largest point of solution slowdown.

CU Aerospace in partnership with the University of Illinois at Urbana-Champaign (UIUC) has developed a novel, ground-up redesign of an NLP solver that takes advantage of high performance parallel computing called the Non-Linear PARallel Optimization Tool (NLPAROPT). NLPAROPT uses the Message Passing Interface (MPI) as well as Parallel Basic Linear Algebra (PBLAS) techniques to carry out traditional NLP solution methods in parallel. Preliminary tests have shown NLPAROPT's ability to reduce the runtime by orders of magnitude when compared to its serial counterpart. Applications to simple problems as well as a multiple shooting trajectory optimization test problem are demonstrated. There remains significant additional avenues for parallelism and improved robustness that should proffer further gains.

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FORMATION FLYING AND RELATIVE MOTION

Session Chairs:

Srinivas R. Vadali, Texas A&M University
Hanspeter Schaub, University of Colorado

The following paper was not available for publication:

AAS 15-653 Paper Withdrawn

AAS 15-531

SPATIAL RESOLUTION IN DENSITY PREDICTION FOR DIFFERENTIAL DRAG MANEUVERING GUIDANCE

David Guglielmo,[*] David Pérez,[†] Riccardo Bevilacqua[‡] and Leonel Mazal[§]

Atmospheric differential drag can be used to control the relative motion of multiple coplanar spacecraft in Low Earth Orbit (LEO), without the use of any propellant, provided that they can vary their ballistic coefficients. However, the variability of the atmospheric density, and therefore the drag acceleration, makes the generation of accurate drag-based guidance a challenging problem. Currently available density models have biased results, causing errors in the drag force estimation. In this work a method for predicting the atmospheric density along the future orbit of a spacecraft is combined with a calibrator used with existing empirical atmospheric models. The combination is used to improve differential drag-based relative maneuvering by adding spatial resolution to atmospheric density prediction methods. This leads to the creation of more realistic guidance trajectories for spacecraft relative maneuvering based on differential drag.

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AAS 15-622

NONLINEAR REDUCED ORDER DYNAMICS OF SPACECRAFT RELATIVE MOTION FOR A CIRCULAR CHIEF ORBIT

Eric A. Butcher[*] and T. Alan Lovell[†]

Nonlinear reduced order models are obtained for spacecraft relative motion in the case of circular chief orbits. First, a nonlinear third order extension of the CWH equations is obtained and a modal transformation is employed that decouples the linear dynamics. Then two techniques, linear-based order reduction and the methodology of nonlinear normal modes, are employed to obtain nonlinear reduced models corresponding to the three modes of the CWH equations. The resulting nonlinear models extend linear modal analysis of the CWH equations to the nonlinear regime valid for larger separation distances and allow for a geometric characterization of the nonlinear dynamics of relative motion.

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AAS 15-623

USE OF NONLINEARITIES FOR INCREASED OBSERVABILITY IN RELATIVE ORBIT ESTIMATION

Jingwei Wang,* Eric A. Butcher† and T. Alan Lovell‡

In this paper, the effects of incorporating nonlinearities in sequential relative orbit estimation are studied for a chief spacecraft in a circular orbit, assuming either range or line-of-sight measurement of the deputy from the chief. The relative motion models used in an extended Kalman filter can be categorized into four cases: first order (HCW equation), second order, third order and full nonlinear. Observability is studied analytically using Lie derivatives and numerically with the observability index and condition number obtained from employing an extended Kalman filter. The results highlight the improving benefits of using higher order nonlinear models.

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AAS 15-640

ESTABLISHING A FORMATION OF SMALL SATELLITES IN A LUNAR FLOWER CONSTELLATION

Lauren McManus[*] and Hanspeter Schaub[†]

The success of previous lunar science missions can be expanded upon by using a constellation of satellites to increase the lunar surface coverage. A constellation could also serve as a communications or GPS network for a lunar human base. Small-sats, deployed from a single mothercraft, are proposed to achieve a lunar constellation. The establishment of this constellation is investigated where the mothercraft does the primary deployment maneuvers. The constellation lifetime and closed-loop maintenance are addressed.

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AAS 15-677

BRIDGING DYNAMICAL MODELING EFFORT AND SENSOR ACCURACY IN RELATIVE SPACECRAFT NAVIGATION

Kohei Fujimoto,[*] Kyle T. Alfriend[†] and Srinivas R. Vadali[‡]

In current practice, the dynamical model in a spacecraft navigation algorithm is often set *ad hoc* without explicit regard for the level of measurement, guidance, or control errors expected. In this paper, we develop methods to quickly survey the trade space between navigation system parameters and dynamical model fidelity. We focus our efforts on forces that have precise deterministic physical models, e.g., the Earth's gravity, such that modeling errors may be regarded as biases. Our approach simplifies the workflow of designing navigation systems by mitigating the need to conduct a large-scale non-linear numerical validation of system performance.

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ANALYTIC SOLUTION FOR SATELLITE RELATIVE MOTION WITH ZONAL GRAVITY PERTURBATIONS

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

A state transition matrix for satellite relative motion including the effects of the higher-degree zonal gravity harmonics is presented. This work extends the earlier development by Gim and Alfriend which considered only the first-order secular and periodic perturbations due to the second zonal harmonic. Deprit's Lie-transform based canonical perturbation theory is used to compute secular, short-period, and long-period perturbations in the orbital elements. Secular effects up to order three and periodic perturbations up to order two due to the zonal harmonics J_2 through J_6 are incorporated into the solution. The methodology presented in this work can be extended to include the second-order secular as well as short-period perturbations for the zonal harmonics up to an arbitrary degree. The improvement in prediction accuracy of relative motion resulting from each of the multiple effects is ascertained by considering projected circular orbit satellite formations.

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AAS 15-747

LIBRATION POINT ORBIT RENDEZVOUS USING LINEARIZED RELATIVE MOTION DYNAMICS AND NONLINEAR DIFFERENTIAL CORRECTION

Sara Case[*]

This paper presents a technique for computing a rendezvous trajectory with a target satellite in a libration point orbit. The chaser satellite completes the rendezvous by executing a series of impulsive maneuvers to travel between waypoints approaching the target satellite. Linearized equations of relative motion of the chaser with respect to the target in the circular restricted three body problem are used to compute the required magnitude and direction of the maneuvers; these results are then refined using differential correction with the nonlinear equations of motion. The performance of this technique is discussed and several rendezvous strategies are evaluated.

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AAS 15-773

CONTINUOUS-TIME MODELING AND CONTROL USING LINEARIZED RELATIVE ORBIT ELEMENTS

Trevor Bennett[*] **and Hanspeter Schaub**[†]

Motivated by the breadth of applications for relative orbit control in formation flying and proximity operations, a new approach to the time-varying Clohessy-Wiltshire (CW) equations is developed. The Lagrangian Brackets variations enable study of invariants in the presence of perturbation accelerations. The Lagrangian Brackets are applied to the constants in the linear CW equations, called Linearized Relative Orbit Elements or LROEs, to provide equations of motion. The geometrical relative motion insights are investigated when drag perturbations are included. In addition, a LROE feedback control law to transition between relative orbits is developed and numerically assessed. The manuscript concludes with relative orbit reconfiguration optimization fundamentals and discussion of additional work.

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AAS 15-790

UNIFORM AND WEIGHTED COVERAGE FOR LARGE LATTICE FLOWER CONSTELLATIONS

Sanghyun Lee,[*] Martín E. Avendãno[†] and Daniele Mortari[‡]

This paper addresses the problem of designing satellite constellations with a large number of satellites on circular orbits. As the number of satellite increases the minimum distance constraint slows down the optimization process. Using the 2-D Lattice Flower Constellations theory with the constraint of having all satellites in the same relative trajectory in any rotating frame (e.g., the Earth) the minimum distance constraint is obtained a priori *if the relative trajectory has no self intersections*. The algorithms to obtain this condition (no self-intersections) is presented. The design parameters of three different configurations made with 200, 289, and 391 satellites Flower Constellations are presented. The coverage of these configurations are shown for specific altitude. These large Lattice Flower Constellations are invariant with respect to the orbital altitude (orbital period). The constellation coverage performance have been optimized using Genetic Algorithms and uniform distribution of points on a sphere.

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ASTEROID AND NON EARTH ORBITING MISSIONS

Session Chairs:

Brent Barbee, NASA Goddard Space Flight Center
Bong Wei, Iowa State University
Jay McMahon, University of Colorado at Boulder
Jeffrey S. Parker, University of Colorado at Boulder

The following papers were not available for publication:

AAS 15-681	Paper Withdrawn
AAS 15-699	Paper Withdrawn
AAS 15-700	Paper Withdrawn
AAS 15-721	Paper Withdrawn
AAS 15-786	Paper Withdrawn

AAS 15-526

NEAR-EARTH ASTEROIDS 2006 RH$_{120}$ AND 2009 BD: PROXIES FOR MAXIMALLY ACCESSIBLE OBJECTS?

Brent W. Barbee[*] and Paul W. Chodas[†]

NASA's Near-Earth Object Human Space Flight Accessible Targets Study (NHATS) has identified over 1,400 of the approximately 12,800 currently known near-Earth asteroids (NEAs) as more astrodynamically accessible, round-trip, than Mars. Hundreds of those approximately 1,400 NEAs can be visited round-trip for less change-in-velocity than the lunar surface, and dozens can be visited round-trip for less change-in-velocity than low lunar orbit. How accessible might the millions of undiscovered NEAs be? We probe that question by investigating the hypothesis that NEAs 2006 RH$_{120}$ and 2009 BD are proxies for the most accessible NEAs we would expect to find, and describing possible future NEA population model studies.

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AAS 15-533

ROSETTA: IMAGING TOOLS, PRACTICAL CHALLENGES AND EVOLUTION OF OPTICAL NAVIGATION AROUND A COMET

David S. Antal-Wokes[*] **and Francesco Castellini**[†]

One challenge faced by ESA's Rosetta mission was developing a generic method of navigation around an unknown body. The image processing Graphical User Interfaces, or GUIs, engaged in continuous optical navigation are examined in this article. GUI-Basic addresses the problem of initially defining landmarks and enabling a heuristic reconstruction of the landmarks and camera. GUI-Fusion enables manual image processing by deriving an appropriate subset of images to aid in identifying all visible landmarks. GUI-Pred is designed for poor imaging conditions, enabling contour-shifting and correcting positions accordingly. The subroutines for the selection processes, predictive tools and *N*-point correction algorithms are derived and examples given, set in the broader context of the cometary phase of the Rosetta mission.

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INDUCED FRAGMENTATION OF ASTEROIDS DURING CLOSE ENCOUNTERS

Bryan Tester[*] and Massimiliano Vasile[†]

We consider the behaviour of rotating binary asteroids as they pass through Earth's Hill sphere, with primary interest in the effect the tidal force on the interaction between the two components of the binary and their post-encounter trajectories. We focus on contact binary asteroids bound by a regolith bridge, using both direct numerical simulation and analytical approaches to investigate the sensitivity of the system to different parameters. We find that the system is most sensitive to the angle between the binary pair and the orbital path, having a significant impact upon the energy change during a fragmentation event. We also give the results of some basic simulations of a deflection attempt on such an object.

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AAS 15-550

PASSIVE VS. PARACHUTE SYSTEM TRADE APPLIED TO THE MULTI-MISSION EARTH ENTRY VEHICLE CONCEPT

Allen Henning,[*] Robert Maddock[†] and Jamshid Samareh[‡]

The Multi-Mission Earth Entry Vehicle (MMEEV) is a flexible vehicle concept based on the Mars Sample Return (MSR) EEV design which can be used in the preliminary sample return mission study phase to parametrically investigate any trade space of interest to determine the best design approach for that particular mission concept. In addition to the trade space dimensions often considered (e.g. entry conditions, payload size and mass, vehicle size, etc.), the MMEEV trade space considers whether it might be more beneficial for the vehicle to utilize a parachute system during descent/landing or not (i.e. fully passive).

In order to evaluate this trade space dimension, a simplified parachute system model, based on inputs such as vehicle size/mass, the payload size/mass and the landing requirements, has been developed. This model is then used in conjunction with analytical approximations of a mission trade space dataset provided by the MMEEV System Analysis for Planetary EDL (M-SAPE) trade space tool, to help quantify the differences between a passive and an active (with parachute) vehicle concept.

Preliminary results over a range of EEV vehicle and mission constraints (including entry conditions, vehicle size, payload mass, and landing requirement) are provided. For most sample return missions, this latter constraint (landing velocity and/or load) is ultimately determined by science considerations (e.g. sample preservation or containment). Regions of the trade space where including a parachute system is clearly more beneficial versus those where a passive vehicle clearly provides a more mass efficient approach, are identified. Where the choice between the two architectures may be less clear, additional considerations, including factors such as overall system reliability; system risk and complexity; and development and testing costs, must also be taken in account.

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TOWING ASTEROIDS WITH GRAVITY TRACTORS ENHANCED BY TETHERS AND SOLAR SAILS

Haijun Shen[*] and Carlos M. Roithmayr[†]

Material collected from an asteroid's surface can be used to increase gravitational attraction between the asteroid and a Gravity Tractor (GT); the spacecraft therefore operates more effectively and is referred to as an Enhanced Gravity Tractor (EGT). The use of tethers and solar sails to further improve effectiveness and simplify operations is investigated. By employing a tether, the asteroidal material can be placed close to the asteroid while the spacecraft is stationed farther away, resulting in a better safety margin and improved thruster efficiency. A solar sail on a spacecraft can naturally provide radial offset and inter-spacecraft separation required for multiple EGTs.

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PLANETARY DEFENSE MISSION APPLICATIONS OF HEAVY-LIFT LAUNCH VEHICLES

George Vardaxis[*] and Bong Wie[†]

This paper expands the previously established capabilities of the Asteroid Mission Design Software Tool (AMiDST) to include launch vehicles currently under development by SpaceX and NASA, in addition to the Delta II, Delta IV, and Atlas V class launch vehicles, for its planetary defense mission applications. A fictional asteroid, designated 2015 PDC, is used as a reference target asteroid to further demonstrate the effectiveness and applicability of the AMiDST for planetary defense mission design and planning. During the 2015 IAA Planetary Defense Conference, the asteroid 2015 PDC was used for an exercise where participants simulated the decision-making process for developing deflection and civil defense responses to a hypothetical asteroid threat. The planetary defense missions considered in this paper are primarily focused on short-warning time scenarios (90 days, 60 days, and 30 days) where a very large (5,000 to 10,000 kg) space system would be launched using heavy-lift launch vehicles such as Delta IV Heavy, Falcon Heavy, or the SLS, to intercept and disrupt the oncoming target asteroid.

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AAS 15-565

SENSITIVITY ANALYSIS OF THE OSIRIS-REX TERMINATOR ORBITS TO RANDOM DE-SAT MANEUVERS

Siamak G. Hesar,[*] Daniel J. Scheeres[†] and Jay W. McMahon[‡]

OSIRIS-REx is NASA's asteroid sample return mission and is aimed for launch in the year 2016 to the asteroid 1999 RQ36. The nominal orbit that is considered for the science phase of the mission is a sun-terminator circular orbit. Sun-terminator orbits are quasi-stable orbits in a solar radiation pressure dominated environment. However, due to highly non-Keplerian dynamics that exist in such an environment, small perturbations can lead to large deviations from the nominal trajectory. Such perturbations arise from errors in de-saturation maneuvers. In this study we analyze the sensitivity of the terminator orbits to the maneuver execution errors and their uncertainties.

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A NEW NON-NUCLEAR MKIV (MULTIPLE KINETIC-ENERGY IMPACTOR VEHICLE) MISSION CONCEPT FOR DISPERSIVELY PULVERIZING SMALL ASTEROIDS

B. Wie,[*] B. Zimmerman,[†] P. Premaratne,[†] J. Lyzhoft[†] and G. Vardaxis[‡]

This paper presents the initial preliminary study results for a new non-nuclear MKIV (Multiple Kinetic-Energy Impactor Vehicle) system that can dispersively pulverize small asteroids (< 150 m) detected with short mission lead times (< 10 years). The proposed MKIV system with its total mass in the range of approximately 5,000 to 15,000 kg can be launched from a single large booster such as Delta IV Heavy, Falcon Heavy or the SLS. Its baseline architecture is comprised of a carrier vehicle (CV) and a number of attached kinetic-energy impactors (KEIs). Near to a target asteroid, the CV will dispense several KEIs and guide them to hit near-simultaneously different locations widely distributed across the target surface area and to cause shock waves to propagate more effectively through the target body. In this paper, a simplified 2D hydrocode simulation model is investigated using both an in-house GPU-accelerated hydrocode and ANSYS AUTODYN commercial software. A multi-target terminal guidance problem and a planetary defense mission design employing heavy-lift launch vehicles are also briefly discussed in support of the MKIV mission concept.

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AAS 15-619

ORGANIZING BALLISTIC ORBIT CLASSES AROUND SMALL BODIES

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

Orbital dynamics around small bodies are as varied as the shape and dynamical states of these bodies. While various classes of orbits have been analyzed in detail, the global overview of relevant ballistic orbits at particular bodies is not easily computed or organized. Yet, correctly categorizing these orbits will ease their future use in the overall trajectory design process. This paper overviews methods that have been used to organize orbits, focusing on periodic orbits in particular, and introduces new methods based on clustering approaches.

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AAS 15-642

SHAPE DEPENDENCE OF KINETIC DEFLECTION FOR A SURVEY OF REAL ASTEROIDS

**Juliana D. Feldhacker,[*] Brandon A. Jones,[†] Alireza Doostan,[‡]
Daniel J. Scheeres[§] and Jay W. McMahon[†]**

The transfer of momentum to an asteroid via kinetic impactor for the purpose of deflection is a stochastic system in which uncertainties are mapped into the effective change in velocity resulting on the asteroid. Additional variation in the imparted velocity is caused by the local topography of the asteroid body. This paper considers uncertainties in the impact location, asteroid shape model, and asteroid material properties for a survey of real asteroid shapes to determine the effect of asteroid topography on kinetic deflection. Several analytical models are introduced, which can significantly improve tractability in the analysis, and the Sobol' sensitivity indices are presented as a means of quantifying the dependence of the uncertainty in the imparted velocity on the uncertainties in the system inputs.

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AAS 15-655

A POLYHEDRAL-POTENTIAL APPROACH FOR EDUCATIONAL SIMULATIONS OF SPACECRAFT IN ORBIT ABOUT COMET 67P/CHURYUMOV-GERASIMENKO

Jason M. Pearl[*] and Darren L. Hitt[†]

The European Space Agency's Rosetta Mission to comet 67P/Churyumov-Gerasimenko (67P/CG) has provided a wealth of detailed, 3-D topological data enabling the reconstruction a digital version of the body. Using this information, a discrete 'polyhedra potential' approach has been taken to develop an a computational testbed for students in advanced astrodynamics courses to examine the irregular 3-D potential field of 67P/CG and the corresponding motion of a spacecraft in its orbit. These computational activities provide students with a valuable experience in appreciating the complexities associated with actual mission trajectory planning in stark contrast to idealized two-body models.

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AAS 15-659

CONTACTLESS ION BEAM ASTEROID DESPINNING

Claudio Bombardelli,[*] Daniel Pastor-Moreno[†] and Hodei Urrutxua[‡]

The paper analyzes the performance of an ion beam shepherd (IBS) spacecraft as a contactless actuator to modify the rotational state of an asteroid. The beam is pointed towards the asteroid with a properly controlled offset distance that maximizes the torque transmitted to the celestial body. Analytical and numerical tools are employed to evaluate the despin performance of the method for asteroids of various shapes and sizes. A simple control strategy to minimize the residual tumbling motion at the end of the despin maneuver is proposed. Results show that the method can be effectively used to despin asteroids of less than 20-30 m diameter in a reasonable time span. In addition, we show that the despinning strategy can be applied to larger, Itokawa-size asteroids in order to obtain a tiny measurable modification of their spin rate as a possible low-cost demonstration of contactless ion beam momentum transfer to a space object.

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AAS 15-665

TETHERED GRAVITY ASSISTED MANEUVERS IN CLOSE APPROACH ASTEROIDS TO ACCELERATE A SPACECRAFT

Antonio F. B. A. Prado[*]

The goal of the present paper is to study the problem of sending a spacecraft to the exterior planets of the Solar System, or even beyond, using a Tethered Sling Shot Maneuver (TSSM) in one of the asteroids that passes close to the Earth. In this type of maneuver the rotation of the spacecraft around the asteroid is made by a tether linking the spacecraft and the asteroid. This type of maneuver can give variations of energy much larger than the ones that come from the gravity assisted maneuvers and, in most cases, this variation of energy is enough to send the spacecraft outside the Solar System. The key element for this maneuver is the velocity of the asteroid around the Sun, because the variation of energy obtained from this maneuver is proportional to this variable. This procedure may become a new form to send spacecrafts away from the orbit of the Earth and have a good potential to generate large savings in fuel expenditure. The ideas presented here are particularly interesting when applied to small satellites, that is a concept that will be used to study the Solar System in the future, because their small masses reduces the requirements related to the strength of the tether. It is also suggested the use of a permanent tether linked to the asteroid, as a form to facilitate the practical aspects of anchoring the tether to the asteroid.

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AAS 15-667

ON THE PROJECTION OF COVARIANCE ELLIPSOIDS ON NON-PLANAR SURFACES

Jay W. McMahon,[*] Nicola Baresi[†] and Daniel J. Scheeres[‡]

This paper presents a methodology for projecting a covariance ellipsoid onto a non-planar surface. In particular, this methodology is useful for determining the statistics of where a spacecraft will land on a small body. Given the high curvature of small bodies, the resulting landing ellipse will be non-Gaussian and non-planar itself, making this projection process a challenging endeavor. We show that the landing ellipse can be computed using our methodology in an order of magnitude less time than a typical Monte Carlo analysis, with a close reproduction of the resulting statistics.

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AAS 15-669

OPTIMIZING SMALL BODY GRAVITY FIELD ESTIMATION OVER SHORT ARCS

**Jay W. McMahon,[*] Daniel J. Scheeres,[†]
Davide Farnocchia[‡] and Steven R. Chesley[‡]**

This paper examines the factors that influence the accuracy to which the gravity field of a small near-Earth asteroid can be estimated based on only a short period of time for dedicated radio science data collection. This is a difficult problem for a number of reasons, including the fact that the gravity field is very weak, the non-gravitational perturbations are relatively more significant, and time and measurement quantity are limited by mission constraints. Therefore it is key that the radio science experiment is designed to be as efficient as possible at obtaining information about the gravity field of the asteroid. The key focus in this analysis is on the orbit size/shape, the measurement quantity, and placement.

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AAS 15-690

ORBIT STABILITY OF OSIRIS-REX IN THE VICINITY OF BENNU USING A HIGH-FIDELITY SOLAR RADIATION MODEL

Trevor W. Williams,[*] Kyle M. Hughes,[†]
Alinda K. Mashiku[‡] and James M. Longuski[§]

Solar radiation pressure is one of the largest perturbing forces on the OSIRIS-Rex trajectory as it orbits the asteroid Bennu. In this work, we investigate how forces due to solar radiation perturb the OSIRIS-REx trajectory in a high-fidelity model. The model accounts for Bennu's non-spherical gravity field, third-body gravity forces from the Sun and Jupiter, as well as solar radiation forces acting on a simplified spacecraft model. Such high-fidelity simulations indicate significant solar radiation pressure perturbations from the nominal orbit. Modifications to the initial design of the nominal orbit are found using a variation of parameters approach that reduce the perturbation in eccentricity by a factor of one-half.

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AAS 15-739

THE EUROPEAN ASTEROID IMPACT MISSION: PHASE A DESIGN AND MISSION ANALYSIS

Fabio Ferrari,[*] Michèle Lavagna,[†] Marc Scheper,[‡]
Bastian Burmann[‡] and Ian Carnelli[§]

AIM is part of a joint collaboration with NASA in the AIDA (Asteroid Impact & Deflection Assessment) mission. The primary goal of AIDA is to assess the feasibility of deflecting the heliocentric path of a Near Earth Asteroid (NEA) binary system, by impacting on the surface of the smaller secondary asteroid of the couple. The work here presented is part of the phase A study, currently performed by OHB System AG, Politecnico di Milano and Spin.Works under the European Space Agency study for phase A/B1. The paper focuses on the mission analysis of AIM spacecraft during the main phases of the mission: interplanetary transfer, rendezvous with the asteroid and close proximity operations.

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ORBITAL DEBRIS AND CONJUNCTION ANALYSIS

Session Chairs:

Liam Healy, Naval Research Laboratories
Glenn Peterson, The Aerospace Corporation

AAS 15-528

EXAMINATION OF POTENTIAL SOURCES OF SMALL HIGH DENSITY PARTICLES IN EARTH ORBIT

Glenn E. Peterson,[*] Alan B. Jenkin[†] and Marlon E. Sorge[‡]

Evidence of high-density man-made steel particles has been observed in returned Shuttle radiators and windows. However, the true physical sources of these particles have not been conclusively identified. This paper examines potential sources (surface degradation of orbiting intact objects, and historical explosions) and their consequences for long-term modeling. It was found that few intact objects have stainless steel surfaces with implications for any surface degradation model, and, if explosions are a source, then the small particles should have decayed out of the environment by the present time.

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AAS 15-534

CONTAINMENT OF MODERATE-ECCENTRICITY BREAKUP DEBRIS CLOUDS WITHIN A MAXIMUM ISOTROPIC SPREADING SPEED BOUNDARY

Brian W. Hansen[*] and Felix R. Hoots[†]

Following the energetic breakup of a satellite, it is important to determine if any other satellites will be at risk from the resulting debris cloud. One method for assessing this risk involves the determination of times when a satellite flies within the boundary of the debris cloud. This analysis seeks to prove that a certain set of boundary fragments will form a surface that continues to contain the interior fragments of a moderate-eccentricity debris cloud evolving over time. Thus, if a satellite is not inside this surface, it will not be at risk from any other debris fragments.

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AAS 15-545

COMPARISON OF NON-INTRUSIVE APPROACHES TO UNCERTAINTY PROPAGATION IN ORBITAL MECHANICS

Chiara Tardioli,[*] Martin Kubicek,[*] Massimiliano Vasile,[†]
Edmondo Minisci[‡] and Annalisa Riccardi[§]

The paper presents four different non-intrusive approaches to the propagation of uncertainty in orbital dynamics with particular application to space debris orbit analysis. Intrusive approaches are generally understood as those methods that require a modification of the original problem by introducing a new algebra or by directly embedding high-order polynomial expansions of the uncertain quantities in the governing equations. Non-intrusive approaches are instead based on a polynomial representations built on sparse samples of the system response to the uncertain quantities. The paper will present a standard Polynomial Chaos Expansion, an Uncertain Quantification-High Dimensional Model Representation, a Generalised Kriging model and an expansion with Tchebycheff polynomials on sparse grids. The work will assess the computational cost and the suitability of these methods to propagate different type of orbits.

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AAS 15-557

DEBRIS RE-ENTRY MODELING USING HIGH DIMENSIONAL DERIVATIVE BASED UNCERTAINTY QUANTIFICATION

Piyush M. Mehta,[*] Martin Kubicek,[†]
Edmondo Minisci[‡] and Massimiliano Vasile[§]

Well-known tools developed for satellite and debris re-entry perform break-up and trajectory simulations in a deterministic sense and do not perform any uncertainty treatment. In this paper, we present work towards implementing uncertainty treatment into a Free Open Source Tool for Re-entry of Asteroids and Space Debris (FOSTRAD). The uncertainty treatment in this work is limited to aerodynamic trajectory simulation. Results for the effect of uncertain parameters on trajectory simulation of a simple spherical object is presented. The work uses a novel uncertainty quantification approach based on a new derivation of the high dimensional model representation method. Both aleatoric and epistemic uncertainties are considered in this work. Uncertain atmospheric parameters considered include density, temperature, composition, and free-stream air heat capacity. Uncertain model parameters considered include object flight path angle, object speed, object mass, and direction angle. Drag is the only aerodynamic force considered in the planar re-entry problem. Results indicate that for initial conditions corresponding to re-entry from a circular orbit, the probabilistic distributions for the impact location are far from the typically used Gaussian or ellipsoids and the high probability impact location along the longitudinal direction can be spread over ~2000 km, while the overall distribution can be spread over ~4000 km. High probability impact location along the lateral direction can be spread over ~400 km.

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AAS 15-584

PETASCALE DISCOVERY OF PASSIVELY CONTROLLED SATELLITE CONSTELLATIONS FOR GLOBAL COVERAGE

**William R. Whittecar,[*] Marc D. DiPrinzio,[†] Lake A. Singh,[*]
Matthew P. Ferringer[‡] and Patrick Reed[§]**

Satellite mission designers have long sought solutions to the global coverage problem using a minimum number of vehicles. Draim designed a four-satellite constellation with elliptical orbits that continuously covers the globe, but orbit perturbations can degrade coverage up to 32% over eight years without significant stationkeeping. This study combines high-fidelity orbit propagation and coverage analysis with many-objective evolutionary algorithms to explore the design space of four-satellite constellations, seeking alternatives to Draim's design that maintain continuous coverage with minimal propellant. Also leveraging massively parallel computing and advanced visual analytics, we have discovered families of sustainable, passively controlled constellations that provide near-continuous worldwide coverage.

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AAS 15-586

TRENDING IN PROBABILITY OF COLLISION MEASUREMENTS

J. J. Vallejo,[*] M. D. Hejduk[†] and J. D. Stamey[‡]

A simple model is proposed to predict the behavior of Probabilities of Collision (P_c) for conjunction events. The model attempts to predict the location and magnitude of the peak P_c value for an event by assuming the progression of P_c values can be modeled to first order by a downward-opening parabola. To incorporate prior information from a large database of past conjunctions, the Bayes paradigm is utilized; and the operating characteristics of the model are established through a large simulation study. Though the model is simple, it performs well in predicting the temporal location of the peak (P_c) and thus shows promise as a decision aid in operational conjunction assessment risk analysis.

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AAS 15-602

POSTERIOR DISTRIBUTION OF AN ORBITAL ENSEMBLE FROM POSITION-ONLY OBSERVATIONS

Liam Healy[*] and Christopher Binz[*]

Unassociated partial-state observations of orbits can provide probabilistic information on the earth orbital environment. A probability density function (pdf) of orbits may be constructed from position-only observations by assuming that velocities are all equally possible subject only to physical constraints. The eccentricity vector can be computed; combined with previously-presented results for other elements, this can be used to derive the pdf over a complete set of state variables. Unassociated position observations from an ensemble of orbits provide a joint pdf by orbital element. The location of sensors and the distribution of orbits affect the quality and utility of the results.

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AAS 15-631

MANEUVER DETECTION WITH EVENT REPRESENTATION USING THRUST-FOURIER-COEFFICIENTS

Hyun Chul Ko[*] and Daniel J. Scheeres[†]

A systematic way of detecting unknown maneuvers is developed by representing an unknown acceleration tied to an event with Thrust-Fourier-coefficients. Event representation using Thrust-Fourier-coefficients can rigorously represent an unknown maneuver by generating an equivalent maneuver with the same secular behavior. By appending 14 Thrust-Fourier-coefficients as solve-for states, the modified sequential filter processes observation data both forwards and backwards in time to detect maneuver onset and termination time respectively. Along with the represented perturbing acceleration, the detection algorithm provides more accurate post-maneuver orbit solutions. A case study of detecting unknown maneuvers with different types of simulated measurement data verifies the presented approach.

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AAS 15-635

NOISE QUANTIFICATION IN OPTICAL OBSERVATIONS OF RESIDENT SPACE OBJECTS FOR PROBABILITY OF DETECTION AND LIKELIHOOD

François Sanson[*] and Carolin Frueh[†]

Charged Couple Device (CCD) technology is widely used in the observation of resident space objects. Even though CCD technology has dramatically improved since the seventies, satellite and star observation is degraded by inevitable noise generation. Successful attempts to estimate the Signal to Noise ratio have been carried out by Newberry and Merline et al. but the recent needs for high precision and reliable observations in satellite tracking lead us to look for improvements in the pre-existing CCD equations. This study aims at critically inspecting the hypotheses used to derive the CCD equation to provide a rigorous derivation of it and comparing the CCD equation to computer run simulations of CCDs. In a second step the expression for the probability of detection is investigated. Subsequently a closed form expression for the object position uncertainty is derived for the use in multi-target tracking algorithms.

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AAS 15-697

REGULARISED METHODS FOR HIGH-EFFICIENCY PROPAGATION

Jacco Geul,[*] Erwin Mooij[†] and Ron Noomen[‡]

Although regularised propagation methods have a good performance (accuracy versus evaluations), they suffer from a number of practical difficulties, such as propagation to a fixed time, making them ill-suited for practical applications. Several methods that address these limitations are proposed, thoroughly discussed, and analysed on diverse test cases. Dromo outperforms the conventional propagation methods significantly. It is shown that regularised methods, through some adaptations, can be successfully applied to different orbit problems. The proposed method is recommended especially for computationally demanding problems.

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ORBITAL DEBRIS ANALYSIS AND UNCERTAINTY PROPAGATION

Session Chairs:

Carolin Frueh, Purdue University
Suman Chakravorty, Texas A&M University

The following papers were not available for publication:

AAS 15-710 Paper Withdrawn
AAS 15-755 Paper Withdrawn

AAS 15-536

USING IN-FLIGHT NAVIGATION INFORMATION TO CREATE A DEFINED 3-D FORMATION OF TWENTY-FOUR DEPLOYED SUB-PAYLOADS[*]

Ernest L. Bowden,[†] Charles G. Kupelian[†] and Brian R. Tibbetts[‡]

The C-REX (Cusp Region EXperiment) sounding rocket mission launched November 24th, 2014, successfully demonstrating a new technique for deploying and releasing a formation of trackable chemicals in a defined 3-dimensional spatial grid comprised of twenty-four sub-payloads. This paper describes the new systems required to create this 3-D formation of sub-payloads in the face of the large trajectory dispersions associated with high altitude sounding rockets and achieve adequate separation within the short 12 minute total flight time. Preliminary results from the C-REX mission show separations of upwards of 40km from the main body, with the formation of sub-payloads being successfully implemented.

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OBSERVABILITY OF SPACE DEBRIS OBJECTS

Carolin Frueh*

In the standard observation of space debris, only a subset of the state (position and velocity) is available in every single observation, e.g. via ground based telescopes or radars. Even if the full state can be sufficiently estimated from multiple observations the information is not sufficient to predict all the non-conservative accelerations acting on that object, because they are body dependent (on such as shape, attitude and surface properties e.g.) rather than simply state dependent. Those accelerations however influence the future state, depending on the object properties, to a larger or lesser extent. However, only the effect of the superposition of all those influences can be measured. Different models can be chosen to simulate these properties. Characterization measurements can give insight into those properties measuring not the astrometric position but the reflected light for example. But these measurements are created by a different superposition of the effects. This paper investigates the observability of all parameters that influence the object dynamics, in order to aid the object propagation and characterization. A redefinition of the measurement function and subsequently the observability is proposed in order to incorporate measurement noise in the observability considerations. It is shown that the measurement noise not only is a carrier of information; observability considerations with measurement noise allow to increase observability based on sensor characteristics.

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AAS 15-617

DISTRIBUTED COMPUTATION FOR NEAR REAL-TIME FOOTPRINT GENERATION

Christopher B. McGrath,[*] Mark Karpenko[†] and Ronald J. Proulx[‡]

It is computationally expensive to generate landing footprints for reentry vehicles. Techniques that utilize parallel computation can therefore significantly decrease computation time. Distributed computing techniques can be used to calculate an entire footprint in almost the same time that it takes a serial method to generate a single footprint point. The resulting speedup is a significant step towards real-time footprint generation. This paper describes two different parallel implementations of a psuedospectral optimal control solver and analyzes the footprint generation speedup achieved by both program architectures.

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ANALYSIS OF HYPER-PSEUDOSPECTRAL TRANSFORMATION OF RANDOM VARIABLES

Paul J. Frontera,[*] Ronald J. Proulx,[†] Mark Karpenko[‡] and I. Michael Ross[§]

Accurate transformation of random variables is required for many estimation algorithms with applications including guidance, navigation, and control (GNC). While the linear transformation of random variables is well understood, nonlinear transformations remain challenging as analytic solutions frequently do not exist and numerical techniques must be employed. Existing approximation methods for nonlinear transformations include linearization, Monte Carlo analysis using a sufficiently large number of samples, and numerical integration using the Unscented Transform. This paper analyzes performance of the Unscented Transform using hyper-pseudospectral points (HS points) compared to existing methods for the nonlinear transformation of random variables.

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AAS 15-709

COLLISION AND RE-ENTRY ANALYSIS UNDER ALEATORY AND EPISTEMIC UNCERTAINTY

Chiara Tardioli[*] **and Massimiliano Vasile**[†]

This paper presents an approach to the design of optimal collision avoidance and re-entry maneuvers considering different types of uncertainty in initial conditions and model parameters. The uncertainty is propagated through the dynamics, with a non-intrusive approach, based on multivariate Tchebycheff series, to form a polynomial representation of the final states. The collision probability, in the cases of precise and imprecise probability measures, is computed considering the intersection between the uncertainty region of the end states of the spacecraft and a reference sphere. The re-entry probability, instead, is computed considering the intersection between the uncertainty region of the end states of the spacecraft and the atmosphere.

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AAS 15-740

A UKF-PF BASED HYBRID ESTIMATION SCHEME FOR SPACE OBJECT TRACKING

Dilshad Raihan A.V[*] and Suman Chakravorty[†]

Optimal and consistent estimation of the state of space objects is pivotal to surveillance and tracking applications. However, the performance of sequential probabilistic inference algorithms in space systems is restricted by non-Gaussianity and nonlinearity associated with orbital mechanics. In this paper, we present a UKF-PF based hybrid filtering framework for recursive Bayesian estimation of space objects. The proposed estimation scheme is designed to provide accurate and consistent estimates when measurements are sparse without incurring a large computational cost. It employs an unscented Kalman filter (UKF) for estimation when measurements are available. When the target is outside the field of view (FOV) of the sensor, the state probability density function (PDF) is updated via a sequential Monte Carlo method. The hybrid filter addresses the problem of particle depletion through a suitably designed transition scheme. Multiple variants of the hybrid filter are considered by modifying the PF-UKF transition. The hybrid filters are employed in three test cases in which a full three dimensional orbital motion model is considered by including the effects of J_2 and atmospheric drag perturbations. It is demonstrated that the hybrid filters can furnish fast, accurate and consistent estimates outperforming standard UKF and particle filter (PF) implementations.

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AAS 15-745

A RANDOMIZED SAMPLING BASED APPROACH TO MULTI-OBJECT TRACKING WITH COMPARISON TO HOMHT

Weston Faber,[*] Suman Chakravorty[†] and Islam I. Hussein[‡]

In this paper, we present a comparison between our recently published randomized version of the finite set statistics (FISST) Bayesian recursions for multi-object tracking with the commonly known Hypothesis Oriented Multiple Hypothesis Tracking (HOMHT) method. We start by revisiting our hypothesis level derivation of the FISST equations in order to appropriately introduce our randomized method, termed randomized FISST (RFISST). In this randomized method, we forgo the burden of having to exhaustively generate all possible data association hypotheses by implementing a Markov Chain Monte Carlo (MCMC) approach. This allows us to keep the problem computationally tractable. We illustrate the comparison by applying both methods to a space situational awareness (SSA) problem and show that as the number of objects and/or measurement returns increases, as does the computational burden. We then show that the RFISST methodology allows for accurate tracking information far beyond the limitations of HOMHT.

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AAS 15-769

SINGULAR MANEUVERS IN ANGLES-ONLY INITIAL RELATIVE-ORBIT DETERMINATION

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

A maneuver performed by either the chief or deputy spacecraft can provide observability in relative-orbit determination using angles-only measurements and linear, Cartesian dynamics model. This paper, however, presents solutions for maneuvers that result in singular measurement equations and therefore do not provide full-state observability. The singular maneuvers produce changes in the relative position that are proportional to the expected line of sight, and thus produce no changes in the measurements. Additionally, the solution covariance and bias in the presence of noisy measurements is analyzed. This analysis provides insight into desirable maneuvers that improve the accuracy of the initial relative-orbit determination.

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SPACE ENVIRONMENT AND SPACECRAFT GUIDANCE, NAVIGATION AND CONTROL

Session Chairs:

Craig McLaughlin, Kansas University
Marcin Pilinski, ASTRA LLC

The following papers were not available for publication:

AAS 15-592 Paper Withdrawn
AAS 15-742 Paper Withdrawn

AAS 15-520

RENDEZVOUS VIA DIFFERENTIAL DRAG WITH UNCERTAINTIES IN THE DRAG MODEL

Leonel Mazal,[*] David Pérez,[†] Riccardo Bevilacqua[‡] and Fabio Curti[§]

At Low Earth Orbits a differential in the drag acceleration between coplanar spacecraft can be used for controlling their relative motion in the orbital plane. Current methods for determining the drag acceleration may result in errors due to the inaccuracy of density models and misrepresentation of the drag coefficient. In this work a novel methodology for relative maneuvering of spacecraft under bounded uncertainties in the drag acceleration is developed. In order to vary the relative drag acceleration, the satellites modify their pitch angle. Two approaches are proposed. First, a dynamical model composed of the mean semi-major axis and argument of latitude is utilized for describing long range maneuvers. For this model, a Linear Quadratic Regulator (LQR) is implemented, accounting for the uncertainties in the drag force. This controller guarantees asymptotic stability of the system up to a certain magnitude of the state vector, which is determined by the uncertainties. Furthermore, based on a cartesian relative motion formulation, a *min-max* control law is designed for short range maneuvers. This provides asymptotic stability under bounded uncertainties. The two approaches are tested in numerical simulations illustrating a long range re-phasing, performed using the LQR controller, followed by a short range rendezvous maneuver, accomplished using the *min-max* controller.

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DRAG COEFFICIENTS AND NEUTRAL DENSITY ESTIMATION FOR THE ANDE SATELLITES

Craig A. McLaughlin,[*] Harold Flanagan[†] and Travis F. Lechtenberg[‡]

The drag coefficients for the spherical Atmospheric Neutral Density Experiment (ANDE) satellites are calculated using different theories and assumptions to characterize the possible variations. Drag coefficients vary with altitude, solar activity, accommodation, and other factors. Satellite laser ranging data are used as observations in a precision orbit determination scheme to estimate density along the ANDE satellite orbits. The effects of using different drag coefficients on the estimated density are examined.

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AAS 15-748

ANALYTICAL ASSESSMENT OF DRAG-MODULATION TRAJECTORY CONTROL FOR PLANETARY ENTRY

Zachary R. Putnam[*] and Robert D. Braun[†]

Discrete-event drag-modulation trajectory control is assessed for planetary entry using the analytical Allen-Eggers approximate solution to the equations of motion. A control authority metric for drag-modulation trajectory control systems is derived. Closed-form relationships are developed to assess range divert capability, identify jettison condition constraints for limiting peak acceleration and peak heat rate. Discrete-event drag-modulation systems with single stages and an arbitrary number of stages are assessed.

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AAS 15-753

HYPERBOLIC RENDEZVOUS AT MARS: RISK ASSESSMENTS AND MITIGATION STRATEGIES

Ricky Jedrey,[*] Damon Landau[†] and Ryan Whitley[‡]

Given the current interest in the use of flyby trajectories for human Mars exploration, a key requirement is the capability to execute hyperbolic rendezvous. Hyperbolic rendezvous is used to transport crew from a Mars centered orbit, to a transiting Earth bound habitat that does a flyby. Representative cases are taken from future potential missions of this type, and a thorough sensitivity analysis of the hyperbolic rendezvous phase is performed. This includes early engine cut-off, missed burn times, and burn misalignment. A finite burn engine model is applied that assumes the hyperbolic rendezvous phase is done with at least two burns.

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AAS 15-760

EFFECTS OF ATMOSPHERIC DENSITY MODELS AND ESTIMATION TECHNIQUES ON UNCONTROLLED RE-ENTRY PREDICTION

Jin Haeng Choi,[*] Deok-Jin Lee,[†] Tae Soo No,[‡] Sangil Ahn,[§]
Okchul Jung[**] and Hyeongjeong Yim[††]

This paper is focused on the effects of atmospheric density models and drag coefficient on the atmospheric re-entry prediction of an uncontrolled space object. For an accurate prediction of the impact time and location, the states of break-up point are obtained from its orbital motion to terminal location of impact. By using the Monte-Carlo method, the break-up event that generates a group of break-up particles is simply modeled with the consideration of empirical wind model. For the analysis of the effects of the density model on re-entry prediction, four difference density models and drag coefficients were used in the prediction of re-entry trajectory and break-up event.

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AAS 15-765

PRELIMINARY DESIGN OF A MULTI-SPACECRAFT MISSION TO INVESTIGATE SOLAR SYSTEM EVOLUTION USING SOLAR ELECTRIC PROPULSION

Carlos M. A. Deccia,[*] Jeffrey S. Parker,[†] Stijn De Smet,[‡]
Jonathan F. C. Herman[‡] and Ron Noomen[§]

This paper discusses a mission design concept that uses high-power solar electric propulsion (SEP) to re-direct one asteroid into the path of another, generating a low-velocity impact as a means of studying solar system evolution. In order to validate existing models and gain further insight in the processes involved, a multi-spacecraft approach is proposed. This concept involves stationing a spacecraft at each asteroid, using them to achieve precise orbits of both asteroids, and one of the spacecraft with high-power SEP to deflect its asteroid into a low-velocity collision with the other. This study will show that it is possible to achieve asteroid collisions with a relative velocity below 10 km/s, allowing direct observations to study solar system dynamics.

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AAS 15-787

DYNAMICAL SUBSTITUTES OF EQUILIBRIUM POINTS OF ASTEROIDS UNDER SOLAR RADIATION PRESSURE

Xiaosheng Xin,[*] Xiyun Hou,[†] Daniel J. Scheeres[‡] and Lin Liu[§]

Previous works have focused on the hovering points or periodic motion for an imperfect solar sail near an asteroid with the Hill approximation. Equilibrium points and the associated invariant manifolds of a rotating nonspherical asteroid has also been investigated and the landing trajectories and maneuver strategies have been designed for specific asteroid. In the current study, we analysed the equivalent equilibrium points, i.e., dynamical substitutes of an asteroid under solar radiation pressure (SRP) in the asteroid rotating frame. The uniformly rotating triaxial ellipsoid is adopted to model the gravitation of the asteroid. First, the equations of motion with SRP included are constructed in the rotating frame and are then expanded with respect to the original equilibrium points without considering SRP to obtain the linearised equation for the dynamical substitutes. The linearised solutions are numerically corrected to compute the dynamical substitute orbits. Second, the stability properties of the dynamical substitutes are inspected by calculating the corresponding eigenvalues of the monodromy matrix. Third, we numerically integrate the unstable dynamical substitutes in the direction of the corresponding unstable vector to find the invariant manifolds that can intersect with the asteroid surface. This may serve as an option for future landing on the asteroid as well as in-situ observation. Throughout our analyses, the parameters of the triaxial ellipsoid model of the asteroid, such as the mass, size and period, and those corresponding to the SRP, such as the size of the solar panel, are all taken into account and varied in order to fully evaluate the possible results.

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AAS 15-815

ORBITAL MANEUVERING SYSTEM DESIGN AND PERFORMANCE FOR THE MAGNETOSPHERIC MULTISCALE FORMATION

Steven Z. Queen,[*] Dean J. Chai[*] and Sam Placanica[*]

The Magnetospheric Multiscale (MMS) mission consists of four identically instrumented, spin-stabilized observatories elliptically orbiting the Earth in a tetrahedron formation. A requirement for the operational success of the mission is the ability for the on-board systems to deliver precise maneuver adjustments. A six degree-of-freedom (6-DOF), closed-loop control system was developed that tracks a time-varying, inertial velocity-target with less than 1% error down to a five millimeter-per-second lower-threshold (3σ). This level of performance is achieved in-part through integrated and dynamically-compensated accelerometer feedback with micro-gravity resolution. System performance is bounded through an extensive Monte Carlo simulation campaign that exercises the multi-body dynamics and non-linear sensitivities, and supported by some initial flight-results.

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AAS 15-818

PHYSICS-BASED ASSIMILATIVE ATMOSPHERIC MODELING FOR SATELLITE DRAG SPECIFICATION AND FORECASTS

Marcin D. Pilinski,[*] Geoff Crowley,[†] Jonathan Wolfe,[‡] Tim Fuller-Rowell,[§] Tomoko Matsuo,[**] Mariangel Fedrizzi,[††] Stan Solomon,[‡‡] Liying Qian,[§§] Jeff Thayer[***] and Mihail Codrescu[†††]

We describe ongoing work to build a comprehensive nowcast and forecast system for specifying orbital drag conditions. The system outputs include neutral density, winds, temperature, composition, and the satellite drag derived from these parameters. This modeling tool is called the Atmospheric Density Assimilation Model or ADAM. ADAM is based on three state-of-the-art coupled models of the thermosphere-ionosphere running in real-time and uses assimilative techniques to produce a thermospheric nowcast. ADAM will also produce 72 hour predictions of the global thermosphere-ionosphere system using the nowcast as the initial condition and using near real-time and predicted space weather data and indices as the inputs. We show here that the model drag nowcast is comparable to the current state-of-the-art empirical models even in a non-assimilative mode. We also show preliminary results of lower-boundary assimilation in the atmospheric model as well as the improvements from using an assimilative specification of storm-time energy inputs. With additional assimilation and tuning, we expect model performance to exceed the performance of current atmospheric models thus lowering the in-track orbit errors associated with Low Earth Orbit predictions.

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