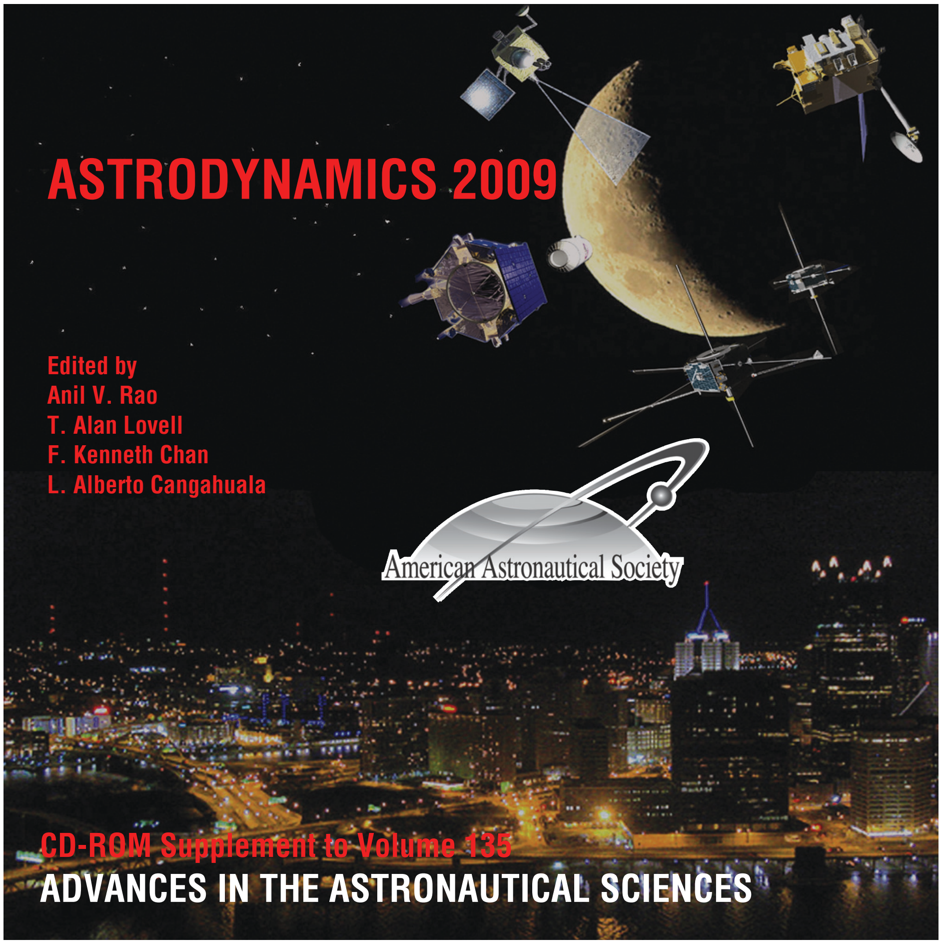
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Edited by
Anil V. Rao
T. Alan Lovell
F. Kenneth Chan
L. Alberto Cangahuala
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ADVANCES IN THE ASTRONAUTICAL SCIENCES

ASTRODYNAMICS 2009

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Dr. Anil V. Rao — University of Florida
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Robert H. Jacobs — Univelt, Incorporated

<u>Front Cover Illustration</u>:

Cover images include the spacecraft that are actively orbiting or *en route* to the Moon at the time of this conference. In clockwise order from top left:

- Chandrayaan-1
- Lunar Reconnaissance Orbiter (LRO)
- Artemis
- Lunar Crater Observation and Sensing Satellite (LCROSS)

Cover illustration design by David Fuller

ASTRODYNAMICS 2009

Volume 135

ADVANCES IN THE ASTRONAUTICAL SCIENCES

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FOREWORD

The 2009 Astrodynamics Conference was hosted by the American Astronautical Society (AAS) and co-sponsored by the American Institute of Aeronautics and Astronautics (AIAA). The conference was held August 9-13, 2009, Pittsburgh, Pennsylvania. There were some 133 papers presented in 20 technical sessions. Session topics included Orbit Determination; Attitude Dynamics, Determination, and Control; Rendezvous, Relative Motion, and Proximity Missions; Special Session: Flight Dynamics for Magnetospheric Survey Missions; Trajectory Optimization; Orbital Dynamics; Planetary, Asteroid, and Deep Space Missions; Special Session: Outer Planet Flagship Mission; Spacecraft Guidance, Navigation, and Control; Conjunction Assessment; Formation Flying; Dynamical Systems Theory Applied to Space Flight; and Satellite Constellations/Tethered Satellites.

These astrodynamics conferences have been held annually since the mid-1960s, managed alternately by the American Astronautical Society and the American Institute of Aeronautics and Astronautics. Every second year the American Astronautical Society publishes the proceedings. The proceedings usually consist of a hard-copy volume or set of volumes plus a microfiche or CD ROM supplement. This volume, *Astrodynamics 2009*, Volume 135, *Advances in the Astronautical Sciences*, consists of three parts totaling about 2500 pages, plus a CD ROM supplement which includes the papers in digital form. All of the available papers appear in full in Volume 135. A chronological index and an author index are appended to the third part of the volume. Papers which were not available for publication are listed on the divider pages of each section in the hard copy volume.

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

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

We commend the general chairs, technical chairs, session chairs and the other participants for their role in making the conference such a success. A special word of thanks is also extended to those who assisted in organizational planning, registration and numerous other functions required for a successful conference.

The current proceedings are valuable in keeping 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.

AAS/AIAA ASTRODYNAMICS VOLUMES

Astrodynamics 2009 appears as Volume 135, *Advances in the Astronautical Sciences*. This publication presents the complete proceedings of the AAS/AIAA Astrodynamics Conference 2009.

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

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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.

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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.

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

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

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

All of these proceedings are available from Univelt, Inc., P.O. Box 28130, San Diego, California 92198 (Web Site: http://www.univelt.com), publishers for the AAS.

Robert H. Jacobs, Series Editor

PREFACE

The 2009 Astrodynamics Specialist Conference was held at the Renaissance Pittsburgh Hotel, Pittsburgh, Pennsylvania, August 9-13, 2009. 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 159 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 133 technical papers presented in 20 sessions on topics related to space-flight mechanics and astrodynamics. The two special sessions (Fight Dynamics for Magnetospheric Survey Missions; and Outer Planet Flagship Mission) were well received and strongly attended.

The meeting included two social events. The first was the Pirates-Cardinals baseball game in the PNC Park on Sunday afternoon August 9 and the second was the Awards Banquet on Tuesday evening August 11 in the Renaissance Pittsburgh Hotel Symphony Ballroom. The featured speaker at the Banquet was Professor Red Whittaker of Carnegie Mellon University's Robotics Institute. He gave an interesting talk about his laboratory's successes in developing autonomous vehicles for the field and their efforts in privately landing a robot on the moon for the Google Lunar X PRIZE.

The editors extend their gratitude to the Session Chairs who made this meeting successful: Matt Berry, Angela Bowes, Russell Carpenter, William Cerven, Thomas Eller, Brian Gunter, Yanping Guo, Robert Hall, Felix Hoots, Kathleen Howell, Peter Lai, Daniele Mortari, Anastassios Petropoulos, Jon Sims, David Spencer, Nathan Strange, Sergei Tanygin, Aaron Trask, and Kenneth Williams. Our gratitude also goes to AAS Space Flight Mechanics Technical Committee Chair T. S. Kelso for his general guidance; and to Subcommittee Chairs: Shannon Coffey, Felix Hoots and John Seago for their advice and support in many facets of the conference. Of special mention is Matt Berry whose invaluable help to the organizing committee is much appreciated.

We would also like to express our thanks to David Fuller for the cover design. Additionally, Paul Stumpf made arrangements for free admission to the Carnegie Science Center for the conference registrants and their families throughout the duration of the conference.

AAS Technical Chair
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AIAA Technical Chair
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AFRL/RVSV

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Jet Propulsion Laboratory

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AAS 09 – 425 Approximate Minimum-Time Control Versus the PEG Control for Lunar Ascent, David G. Hull

SESSION 16: CONJUNCTION ASSESSMENT II

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AAS 09 – 412 Examination of Nonlinearity Based on the Second Order Expansion of the Orbit State Transition, Sergei Tanygin

AAS 09 – 413 Re-Examining Probability Dilution, Joseph H. Frisbee, Jr.

AAS 09 – 414 Analytic Launch Collision Avoidance Methodology, Felix R. Hoots

AAS 09 – 415 Anti-Satellite Engagement Vulnerability, Salvatore Alfano

AAS 09 – 416 Space Situation Monitoring Laboratory: An Integrated Web-Based Environment for Space Environment Information and Analysis, Justin F. McNeill, Jr., John M. Coggi, William H. Ailor, Thaddeus O. Cooper, Raymond L. Swartz, Jr. and Russell P. Patera

SESSION 17: SATELLITE CONSTELLATIONS/TETHERED SATELLITES

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AAS 09 – 419 Long-Term Stability of Flower Constellations under Planetary Oblateness, Troy A. Henderson and Martín Avendaño

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SESSION 18: TRAJECTORY OPTIMIZATION III

AAS 09 – 424 An Assessment of Multiple Satellite-Aided Capture at Jupiter, Alfred E. Lynam, Kevin W. Kloster and James M. Longuski

AAS 09 – 426 An Optimal Initial Guess Generator for Entry Interface Targeters, Juan S. Senent

AAS 09 – 427 Constrained Optimal Orbit Design for Earth Observation Satellites Based on User Requirements, Sharon D. Vtipil and Brett Newman

AAS 09 – 428 Broad Search and Optimization of Solar Electric Propulsion Trajectories to Uranus and Neptune, Damon Landau, Try Lam and Nathan Strange

AAS 09 – 429 Autonomous Multi-Rover Trajectory Planning Using Optimal Control Techniques, Michael A. Hurni, Pooya Sekhavat and I. Michael Ross

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AAS 09 – 433 Spacecraft Trajectory Design for Tours of Multiple Small Bodies, Brent William Barbee, George W. Davis and Sun-Hur Diaz

AAS 09 – 434 Repeated Shadow Track Orbits, Ahmed Gad and Ossama Abdelkhalik

AAS 09 – 435 Leveraging Flybys of Low Mass Moons to Enable an Enceladus Orbiter, Nathan J. Strange, Stefano Campagnola and Ryan P. Russell

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AAS 09 – 439 Ballistic Coefficient and Density Estimation, Craig A. McLaughlin, Andrew Hiatt, Eric Fattig and Travis Lechtenberg

AAS 09 – 440 Mean Element Propagations Using Numerical Averaging, Todd A. Ely

AAS 09 – 441 Arbitrary Order Vector Reversion of Series and Implicit Function Theorem, James D. Turner, Manoranjan Majji and John L. Junkins

AAS 09 – 442 Earth-Moon Trajectory Design Using Lagrange Implicit Function Theorem, Manoranjan Majji, James D. Turner and John L. Junkins

AAS 09 – 443 Low-Energy Ballistic Transfers to Lunar Halo Orbits, Jeffrey S. Parker

AAS 09 – 444 State Transition Matrix Approximation Using a Generalized Averaging Method, Yuichi Tsuda and Daniel J. Scheeres

AWARDS BANQUET PRESENTATION

Featured Speaker, William "Red" L. Whittaker (Abstract Only)

WITHDRAWN OR NOT ASSIGNED

AAS 09 – 306, 308, 315, 320, 336, 361, 383, 401, 410, 430, 437

SESSION 1: ORBIT DETERMINATION
Chair: Dr. Thomas Eller, Astro USA, LLC

AAS 09 – 301
Improved Radar Cross-Section "Target-Typing" for Spacecraft

M. D. Hejduk, SRA International

Statistical histories of radar cross-section (RCS) data of satellites are used widely, both for the main application of tracking radar optimization and for tangential uses such as satellite characterization, size estimation, and observation correlation. The Swerling target typing models, however, have not evolved since 1954, when Peter Swerling's two chi-squared PDFs, based on the examination of aircraft data, were first proposed. In an earlier restricted paper only recently published, Swerling repudiated his previous position and advocated a broader set of types, which included additional chi-squared forms and the lognormal distribution. Other recent studies also support the use of lognormal distributions, suggesting that a systematic investigation of target typing for spacecraft is in order. Hit-level RCS histories from the Eglin FPS-85 spacetrack radar on over 8000 objects were obtained and, after appropriate filtering, were examined with the empirical distribution function (EDF) goodness-of-fit technique to determine conformity to the classical two Swerling target type models, an expanded set of chi-squared models including Swerling's own recommendations and other promising variants, and the lognormal distribution. The results revealed that, contrary to the author's expectations, the traditional Swerling types fared reasonably well, adequately representing some 35% of the objects; and the addition of the expanded chi-squared types increased this number to 46%. The lognormal distribution can provide about the same marginal gain, accounting uniquely for about 10% of the objects tested; but its solo performance against the entire dataset reached only the 25% figure, indicating that it in no way is a good replacement candidate for the traditional Swerling types. Future research should thus focus on the some 42% of objects that cannot be represented by any one the chi-squared or lognormal distributions to determine whether a new canonical distribution type should be introduced.

AAS 09 – 302
Satellite Collision Detection and Avoidance Using Star Trackers

Reza Raymond Karimi, Troy A. Henderson and Daniele Mortari,
Texas A&M University

A novel method of collision detection and avoidance is presented based on on-orbit orbit determination. A star tracker on-board a satellite with known orbit parameters is used to determine the orbit of an unknown object. The orbit determination method is based on multiple line-of-sight measurements only. The object is then tracked to predict the time and location of a potential collision. The effects of measurement error and propagation error are discussed. Multiple orbit types are tested and the results presented, along with an analysis of the required number of observations and time between observations for accurate results.

AAS 09 – 303

Initial Orbit Design for Regional Coverage

Ossama Abdelkhalik and Ahmed Gad, Michigan Technological University.

Motivated by the need of optimal orbit design algorithms for remote sensing space missions, the problem of orbit design to cover given set of ground sites, within a constraint time frame, is addressed. The objective is to calculate an orbit such that the spacecraft's Field of View (FOV) covers each of the sites, at least once, within a given time frame. First, the problem is addressed assuming no FOV (forcing the ground track of the spacecraft to pass exactly through the ground sites.) Two solution algorithms have been developed for this case. The first algorithm finds the exact orbit; the second algorithm calculates an approximate solution. The approximate solution can be used as an initial guess in the first algorithm for effective search for the exact solution. Second, the problem is addressed taking into consideration the spacecraft's FOV. Numerical examples are presented for both cases.

AAS 09 – 304

Covariance Realism

David A. Vallado, Center for Space Standards and Innovation;
John H. Seago, Analytical Graphics, Inc.

Covariance information from orbit determination is being relied upon for space operations now more than ever. There have been scattered claims and discussions of realistic covariance, but not enough detailed studies to demonstrate the actual performance against independent references using real data. This paper discusses some statistical tests that could be used to help study predicted covariance accuracy. To illustrate the methods, the authors estimate prediction error by comparing predictions to a precision orbit estimated after the fact. The predicted covariance is analyzed relative to the sample error estimates using the methods described.

AAS 09 – 305

Generalized Covariance Analysis of Additive Divided—Difference Sigma—Point Filters

J. Russell Carpenter, F. Landis Markley, NASA Goddard Space Flight Center;
Sun Hur-Diaz, Emergent Space Technologies, Inc.

The divided-difference sigma-point filter is a sequential estimator that replaces first-order truncations of Taylor series approximations with second-order numerical differencing equations to approximate nonlinear dynamics and measurement models. If the process and measurement noise enter the system additively, several simplifications are possible, including a substantial reduction in the number of sigma-points. As a consequence of the additive noise assumption, a generalized covariance analysis approach that partitions the contributions to the total error of a priori, process, and measurement noise may be applied to the additive divided-difference sigma-point filter. The Cholesky decompositions of the true and formal initial covariances provide true and formal a priori Cholesky factors, and true and formal measurement and process Cholesky partitions are initialized to zero. Two sets of sigma points, truth and formal, are spawned and propagated from the joint set of all three partitions for each. Divided differences are separately extracted from each partition, and factorized to derive time updates for each partition separately, as well as merged to form propagated states. This process is repeated for the measurement update, with a filter gain similarly derived from a joint set of all three partitions. The states ignored by the filter are not updated by this gain. The entire algorithm is formulated using only Cholesky factors. As an example, a simulated highly elliptical orbit is estimated from nonlinear Global Positioning System measurements. In this example, there is a significant nonlinearity at perigee.

AAS 09 – 306

Paper Withdrawn

AAS 09 – 307

Impact of Electric Propulsion Uncertainty on Orbit Prediction

Peter Zentgraf and Sven Erb, ESA/ESTEC

This paper analyses the achievable performance of the orbit prediction for a geostationary satellite using clusters of electrical propulsion (EP) thrusters for station-keeping and a star tracker based attitude control system. The challenge in the orbit prediction is that the real electrical propulsion thrust is known with limited accuracy only. In combination with thrust pointing errors, these inaccuracies can accumulate to large orbit position errors during long low thrust burn arcs. In the proposed paper the discrepancy between real and predicted satellite position will be determined in terms of probability and as a worst case scenario.

AAS 09 – 308

Paper Withdrawn

SESSION 2: ATTITUDE DYNAMICS, DETERMINATION AND CONTROL I
Chair: Dr. Sergei Tanygin, Analytical Graphics, Inc.

AAS 09 – 309
Constrained Time-Optimal Slewing Maneuvers for Rigid Spacecraft

Robert G. Melton, Pennsylvania State University

Time-optimal slewing for orbiting astronomical observatories such as the Swift gamma-ray burst detector must include constraints to protect delicate optical sensors from accidental exposure to high-intensity sources such as the Sun, Earth and Moon. This paper considers the problem of slewing a spacecraft in minimum time in order to align an onboard telescope with a particular target, with one or more path-constraints that maintain a minimum angular distance between the optical sensor axis and the high-intensity sources. The problem is solved via a pseudospectral method, with solutions showing a relatively simple control-switching structure.

AAS 09 – 310
Using Underspecification to Eliminate the Usual Instability of Digital System Inverse Models

Yao Li and Richard W. Longman, Columbia University

Iterative learning control aims to achieve high precision tracking by learning from hardware experience performing a desired maneuver. Spacecraft applications relate to repeated scanning maneuvers. There is a fundamental difficulty that the inverse of a digital system is very often unstable, which makes finding the input needed to produce zero error correspond to the solution of an unstable system. Five candidates for methods to address this problem are investigated, which do not ask for zero error at all time steps. Previous work suggested asking for zero error every other step. This approach is examined in detail here, and it is shown that under certain conditions there can still be difficulties. Methods are suggested to address this new situation. Finally, ILC design methods using quadratic cost functions are presented to make use of the information obtained, so that the ILC inverse problem is well posed and intersample error can be kept small.

AAS 09 – 311

Dynamically Driven Helmholtz Cage for Experimental Magnetic Attitude Determination

Andrew Klesh, Sheryl Seagraves, Matt Bennett, Dylan Boone, James Cutler, University of Michigan; Hasan Bahcivan, SRI International

The Radio Aurora Explorer (RAX) is a small, NSF-sponsored spacecraft being designed, built, and tested by students at the University of Michigan for launch in December 2009. The RAX team has created a dynamically-controlled Helmholtz cage to characterize and calibrate magnetic sensors while serving as an analog-orbit mission simulator. The Helmholtz cage is capable of automatically simulating entire orbits in real-time through the use of Satellite Tool Kit and MATLAB, enabling the team to validate its primary attitude sensor in the lab. This paper presents the design, construction, and capabilities of the RAX Helmholtz cage through experimental and operational results.

AAS 09 – 312

A Direct Method for Identifying Linear Time-Varying State-Space Models

Minh Q. Phan, Dartmouth College; Richard W. Longman, Columbia University; Jer-Nan Juang. National Cheng-Kung University

This paper presents a direct method to identify linear discrete time-varying (LTV) state-space models from input-output data. Unlike previous indirect methods that either work through the observer Markov parameters or a canonical representation, this method computes the time-varying state-space matrices directly from input-output data in one linear step. The input-output data are used to form the state variables from which the LTV state-space models are derived. A key byproduct of this formulation is a new canonical state-space representation where the current-time state-space matrices depend only on the coefficients of the current-time input-output model. The paper also shows how to perform model reduction on the identified time-varying state-space models. Numerical examples are used to illustrate this direct LTV state space identification method.

AAS 09 – 313

Comparison of State-of-The-Art Steering Logics for Control Moment Gyroscopes

Frederick A. Leve, Josue D. Munoz, Norman G. Fitz-Coy, University of Florida; George A. Boyarko, Air Force Research Laboratory

This manuscript compares four state-of-the-art steering logic methods for internal singularity avoidance and escape. The methods addressed in this paper are: (i) Generalized Inverse Steering Logic (GISL), (ii) Feedback Steering Law (FSL), (iii) Inner Product Index (IPI), and Hybrid Steering Logic (HSL). The methods are applied to an attitude control system consisting of four single gimbal control moment gyroscopes (SGCMGs) in a pyramid arrangement which is known to have internal singularities. Comparisons of the methods are based on their effectiveness in addressing the following metrics: torque error for given maneuvers, gimbal rate history, maneuver completion time, and number and duration of singularity encounters.

AAS 09 – 314

Adaptive Angular Velocity Estimator

Bong Su Koh and Daniele Mortari, Texas A&M University

An adaptive filtering technique to estimate the angular velocity is presented for spacecraft with no gyros. The basic idea relies on the fact that, as long as the angular velocity does not change direction, the dynamics of the quaternion describing the attitude evolution, constraints the quaternion itself on a 3-D hyperplane. This paper, using some properties of Ortho-skew matrices and decomposition of orientation into rotations in 4-D space, shows how to identify this hyperplane and how to extract the angular velocity information from a series of subsequent quaternions. Specifically, the direction of the angular velocity is derived from the instantaneous quaternion's plane of rotation while the modulus is estimated by nonlinear least-squares technique using angles between quaternions. Motivation comes from the possibility to estimate the angular velocity when the spacecraft is performing fast maneuvers using star trackers data, only, and/or to provide Kalman filters with good initial angular velocity estimates.

AAS 09 – 315

Paper Withdrawn

SESSION 3: RENDEZVOUS, RELATIVE MOTION AND PROXIMITY MISSIONS

Chair: Dr. Aaron Trask, Apogee Integration

AAS 09 – 316

Optimization of a Spacecraft Maneuver to Dock with a Tumbling Object

George A. Boyarko, Oleg A. Yakimenko and Marcello Romano,
Naval Postgraduate School

This paper considers the problem formulation and numerical solution of the optimal close range rendezvous problem of two spacecraft, one of which is passive and freely tumbling. It first analyses the existing approaches that are limited to simplified models and control strategies. It then addresses the development of the complete three-dimensional twenty-state model of two-spacecraft rendezvous with the chaser spacecraft having body mounted translational thrusters. This work expands the previous work by the authors, so that the optimal control problem is now formulated based on three separate performance indices, minimum-energy, minimum-control and minimum-time and solved with one of the direct (pseudospectral) methods. The costate equations are presented as well as the terminal variations due to transversality which are used to verify the optimality of the solution obtained from the direct method. The paper provides rigorous analysis of the model, results and formulation of the optimal control problem for matching position and velocity of the docking point on each spacecraft as well as spacecraft attitude and angular rate.

AAS 09 – 317

Optimal Control for Proximity Operations and Docking

Daero Lee and Henry Pernicka, Missouri University of Science and Technology

This paper proposes optimal control techniques for determining translational and rotational maneuvers that facilitate proximity operations and docking. Two candidate controllers that provide translational motion are compared: A state-dependent Riccati equation controller is formulated from the nonlinear relative motion dynamics, and a linear quadratic tracking controller is formulated from the linearized relative motion. A linear quadratic Gaussian controller using star trackers to provide quaternion measurements is designed for precision attitude maneuvering. The attitude maneuvers are evaluated for different final axis alignment geometries depending on the approach distance. A six degree-of-freedom simulation demonstrates that the controllers perform proximity operations and docking successfully.

AAS 09 – 318

Linear State-Space Models for J2-perturbed Satellite Relative Motion

Srinivas R. Vadali, Texas A&M University

This paper presents the derivations of linear differential equations for modeling perturbed satellite relative motion dynamics. In the first part of this paper a linear model is obtained for the evolution of the relative motion in a rotating Cartesian coordinate system. This model is developed using expressions for the secular drift rates and the short-period variations of the orbital elements of the reference satellite. The secular in-track linearization error of the model for the case of a mean circular orbit is shown to be consistent with its analytical estimate for the unperturbed problem. The relative state linearization errors for eccentric orbits show reasonable growth rates. The second part of the paper derives a nonhomogeneous linear model in a curvilinear coordinate system. The second model, simplified for the circular reference orbit, is shown to capture more of the nonlinear effects than does the relative Cartesian coordinate model.

AAS 09 – 319

Guidance, Navigation and Control System for Autonomous Proximity Operations and Docking

Daero Lee and Henry Pernicka, Missouri University of Science and Technology

This study develops an integrated guidance, navigation and control system for proximity operations and docking of a spacecraft. The translational maneuvers are determined through the integration of the state-dependent Riccati equation control formulated by the nonlinear relative motion dynamics and the relative navigation using a Lidar and a vision sensor system, where a sensor mode change is done according to the approach distance in order to provide efficient navigation. The Clohessy-Wiltshire equations are used to determine the proper transfer time, reference trajectory, required delta V. The attitude maneuvers, determined from a linear quadratic Gaussian-type control using star trackers, provide the precise attitude control and robustness to the uncertainty of the moment of inertia. A six-degree of freedom simulation demonstrates the effectiveness of the integrated system.

AAS 09 – 320

Paper Withdrawn

AAS 09 – 321

Hypercomplex Eccentric Anomaly in the Unified Solution to the Relative Orbital Motion

Daniel Condurache and Vladimir Martinusi,
Technical University "Gheorghe Asachi" Iasi, Romania

The present work presents an approach to the relative orbital motion by using hypercomplex numbers. An extension to this notion is used for vectors, by introducing the hypercomplex vector in the same way as hypercomplex numbers are defined. The solution to the relative orbital motion is offered in all possible situations (it stands for any Keplerian reference or targeted trajectories). A unified view on the relative orbital motion is suggested, by generalizing the previous approaches. The solution is offered to the nonlinear model of the relative motion and it is expressed in a coordinate-free hypercomplex vectorial closed form. The key element of this approach is the hypercomplex eccentric anomaly, introduced via a Sundman-like vectorial regularization.

AAS 09 – 322

From Elliptic Restricted Three-Body Problem to Tschauner-Hempel Equations: A Control Strategy Based on Circular Problems

Mai Bando and Akira Ichikawa, Kyoto University

This paper considers halo orbit control for the Earth-moon elliptic restricted three-body problem. Expressing equations of motion with true anomaly, Lagrangian points are defined and a halo orbit control problem at the L_2 point is discussed. By the change of control variables, constant feedback controllers are designed which maintain a halo orbit of the circular restricted problem. Considering equations of motion relative to the moon, and letting the mass of the moon go to zero, the equations of relative motion along an eccentric orbit are derived. Then formation and reconfiguration problems are formulated, and feedback controllers, based on the Hill-Clohessy-Wiltshire systems, are designed from the point of view of L_1-norm minimization.

SESSION 4:
SPECIAL SESSION: FLIGHT DYNAMICS FOR MAGNETOSPHERIC SURVEY MISSIONS
Chair: Dr J. Russell Carpenter, NASA GSFC

AAS 09 – 323

Magnetospheric Multi-Scale Mission's Orbit Propagation Sensitivity to Navigation Errors

J. Russell Carpenter, NASA Goddard Space Flight Center

The objective of this paper is to address a need for onboard navigation solutions to propagate accurately, in the context of a formation of satellites in highly elliptical orbits that will study magnetic reconnection. The onboard navigation function is not intended to perform state prediction; rather, it produces definitive states that ground operators will use to generate flight dynamics and science products. Many of these products, such as maneuver plans, conjunction predictions, and tracking acquisition plans, require predictive states. In particular, the paper examines relationships between predictive navigation accuracy and the time between previously unscheduled maneuvers. Planning for such maneuvers, which are needed for formation maintenance and collision avoidance, should accommodate a trade between false alarms and missed detections, and must also meet operational constraints on maneuver frequency. The paper shows how these trades relate to secular growth in the achieved formation states and predictive navigation errors. These relationships refine previous results by including the effect of Earth's oblateness on secular growth of knowledge and execution errors.

AAS 09 – 324

Magnetospheric Multiscale Mission (MMS) Phase 2b Navigation Performance

Paige Thomas Scaperoth and Anne Long, a.i. solutions, Inc.;
Russell Carpenter, NASA Goddard Space Flight Center

The Magnetospheric Multiscale (MMS) formation flying mission, which consists of four spacecraft flying in a tetrahedral formation, has challenging navigation requirements associated with determining and maintaining the relative separations required to meet the science requirements. The baseline navigation concept for MMS is for each spacecraft to independently estimate its position, velocity and clock states using GPS pseudorange data provided by the Goddard Space Flight Center-developed Navigator receiver and maneuver acceleration measurements provided by the spacecraft's attitude control subsystem. State estimation is performed onboard in real-time using the Goddard Enhanced Onboard Navigation System flight software, which is embedded in the Navigator receiver. The current concept of operations for formation maintenance consists of a sequence of two maintenance maneuvers that is performed every 2 weeks. Phase 2b of the MMS mission, in which the spacecraft are in 1.2 x 25 Earth radii orbits with nominal separations at apogee ranging from 30 km to 400 km, has the most challenging navigation requirements because, during this phase, GPS signal acquisition is restricted to less than one day of the 2.8-day orbit. This paper summarizes the results from high-fidelity simulations to determine if the MMS navigation requirements can be met between and immediately following the maintenance maneuver sequence in Phase 2b.

AAS 09 – 325

Magnetospheric MultiScale (MMS) Mission Commissioning Phase Orbit Determination Error Analysis

Lauren R. Chung, Stefan Novak, Anne Long, a.i. solutions, Inc.;
Cheryl Gramling, NASA Goddard Space Flight Center

The Magnetospheric MultiScale (MMS) mission commissioning phase starts in a 185 km altitude x 12 Earth radii (R_E) injection orbit and lasts until the Phase 1 mission orbits and orientation to the Earth-Sun line are achieved. During a limited time period in the early part of commissioning, five maneuvers are performed to raise the perigee radius to 1.2 R_E, with a maneuver every other apogee. The current baseline is for the Goddard Space Flight Center Flight Dynamics Facility to provide MMS orbit determination support during the early commissioning phase using all available two-way range and Doppler tracking from both the Deep Space Network and Space Network. This paper summarizes the results from a linear covariance analysis to determine the type and amount of tracking data required to accurately estimate the spacecraft state, plan each perigee raising maneuver, and support thruster calibration during this phase. The primary focus of this study is the navigation accuracy required to plan the first and the final perigee raising maneuvers. Absolute and relative position and velocity error histories are generated for all cases and summarized in terms of the maximum root-sum-square (RSS) consider and measurement noise error contributions over the definitive and predictive arcs and at discrete times including the maneuver planning and execution times. Details of the methodology, orbital characteristics, maneuver timeline, error models, and error sensitivities are provided.

AAS 09 – 326

MMS Separation and Commissioning Phase Maneuvers

Trevor Williams, NASA Goddard Space Flight Center

The four Magnetospheric MultiScale (MMS) spacecraft are launched in a stack, and released sequentially by identical sets of springs. They then enter a four-month commissioning phase, during which they must: raise the perigee of their highly elliptical orbits from the initial altitude of 185 km, to avoid any possibility of subsequent imminent deorbit from lunisolar perturbations; deploy wire booms and other appendages; calibrate experiments, thrusters and navigation systems; and enter into the initial tetrahedron formation for science observations around apogee. This paper will discuss the design of the various maneuvers required during the commissioning phase, starting with the separation maneuvers.

AAS 09 – 327

Launch Window Opportunity Assessment for the Magnetospheric MultiScale Mission

Laurie M. Mann and Jason Tichy, a.i. solutions, Inc.;
Cheryl J. Gramling, NASA Goddard Space Flight Center

The Magnetospheric MultiScale (MMS) Mission is a tetrahedral formation mission designed to study magnetic reconnection in the Earth's magnetosphere. To sample these regions of interest, the MMS mission will be divided into two main science phases: Phase 1 and Phase 2 with 1.2 Re $\times$ 12 Earth Radii (Re) and 1.2 Re $\times$ 25 Re orbits, respectively. This paper focuses on quantifying the MMS yearly launch window opportunities defined by the associated science and operating parameters and constraints. In addition to the seasonal variation limitation, the MMS reference orbit design has other restrictions such as conflicting requirements between science goals and engineering constraints. This paper will present the MMS launch window opportunity assessment method, assessment results, and an analysis of the orbit perturbation effects on various science and engineering constraints. The impact of initial launch conditions on the implementation of NASA spacecraft disposal requirements will also be considered.

AAS 09 – 328

Overview of the Magnetospheric MultiScale Formation Flying Mission

Cheryl J. Gramling, NASA Goddard Space Flight Center

The Magnetospheric Multi-Scale (MMS) Mission is a tetrahedral formation mission designed to study magnetic reconnection in the Earth's magnetosphere. To sample these regions of interest, the MMS mission will be divided into two main science phases: Phase 1 and Phase 2 with 1.2 $\cdot$ 12 Earth Radii (R_E) and 1.2 $\cdot$ 25 R_E orbits, respectively. This paper provides an overview of the MMS spacecraft and the engineering and science constraints that affect the mission design.

AAS 09 – 329

Apogee Raising Technique for the Magnetospheric Multiscale Formation Flying Mission

Craig E. Roberts, Jason Tichy, a.i. solutions, Inc.;
Cheryl J. Gramling, NASA Goddard Space Flight Center

The NASA Goddard Space Flight Center's Magnetospheric Multiscale (MMS) program involves a four-spacecraft tetrahedral formation flying mission intended for launch in 2014. The mission's high Earth orbits are designed to provide repeated excursions through the magnetosphere and magnetotail for measurement of interaction phenomena between the solar wind and magnetosphere, including magnetic reconnection events. The first of two main science mission phases requires a 1.2 by 12 Earth radii (Re) orbit, while the second phase requires a 1.2 by 25 Re orbit. A transition between the two science phases is for independently raising the apogees of the four spacecraft to 25 Re in stages, followed by re-initialization of the tetrahedral formation. A variety of stringent operational requirements and constraints, plus design features of these spinning spacecraft, pose significant challenges to the apogee raising design. This paper has two main parts. The first part focuses on the strategy and methodology for, and the solutions to, the apogee raising design problem. The second part presents and discusses nominal solutions to the problem of recovery from off-nominal finite burns and maneuver contingency scenarios.

AAS 09 – 330

Optimal Control and Near Optimal Guidance for the Magnetospheric Multiscale Mission (MMS)

Steven P. Hughes, NASA Goddard Space Flight Center

In this paper we present a method for fuel optimal formation control of the Magnetospheric Multiscale Mission (MMS). MMS is a NASA mission[1] that employs 4 spacecraft that must maintain a near-regular tetrahedron in a region centered about apogee of a highly elliptic orbit. The method employs nonlinear parameter optimization to minimize total delta V while simultaneously satisfying guidance, delta V equalization, periodicity, eccentricity, and close approach constraints among others. The proposed approach is fully nonlinear, accommodates orbital perturbations, and is applicable to multiple flight regimes including circular, highly elliptic, hyperbolic, and libration point orbits. Furthermore, the method is applicable to small formations and large constellations. Optimal solutions for MMS are presented that illustrate the fuel savings for various tetrahedron formations.

AAS 09 – 331

Conjunction Assessment for the Magnetospheric Multi-Scale (MMS) Formation

David McKinley and David Rohrbaugh, a.i. solutions, Inc.;
Russell Carpenter, NASA Goddard Space Flight Center

The highly elliptical orbit of the MMS formation-flying mission presents a unique conjunction assessment environment. The MMS spacecraft will spend part of its highly elliptical orbit in a debris-free environment at apogee while transitioning through densely populated regions such as the geo belt and LEO at perigee. An analysis was performed to characterize the debris environment that MMS will encounter and estimate the number of Risk Mitigation Maneuvers (RMM) that could potentially be required. Additionally, an assessment of the GSFC Conjunction Assessment (CA) tool suite was performed to determine its applicability for performing conjunction assessment for the MMS mission.

SESSION 5: TRAJECTORY OPTIMIZATION I
Chair: Jon Sims, Jet Propulsion Laboratory

AAS 09 – 332

An Overview of Three Pseudospectral Methods for the Numerical Solution of Optimal Control Problems

Divya Garg, Michael A. Patterson, William W. Hager, Anil V. Rao,
University of Florida; David A. Benson, Charles Stark Draper Laboratory, Inc.,
Cambridge, MA; Geoffrey T. Huntington, Blue Origin LLC

An overview is presented of three different pseudospectral methods based on collocation at Legendre-Gauss (LG), Legendre-Gauss-Radau (LGR), and Legendre-Gauss-Lobatto (LGL) points. In each scheme presented in this paper, (1) the state at the final time can be expressed in terms of a quadrature rule associated with the collocation points, (2) the state at the initial time is approximated by interpolation, and (3) the control and the state are approximated at the collocation points. The LG-based and LGR-based schemes presented here employ polynomials to approximate the state that are the same degree as the number of collocation points. In the corresponding LGL scheme, the state approximation is a polynomial that is one degree lower than the number of collocation points. Each of these scheme can be expressed in either a differential or an integral formulation. The LG and LGR differentiation and integration matrices are invertible, and the differential and integral versions are equivalent. The LGL differentiation matrix is singular and the equivalence between the differential and integral version is lost. For each scheme, the transformation between the KKT multipliers of the discrete nonlinear programming problem and costates of the continuous optimal control problem is developed. The LGL collocation is the only scheme for which the differentiation matrices for the state and the costate dynamics are the same. An example is used to assess the accuracy and features of each collocation scheme.

AAS 09 – 333

A Learning Approach to Sampling Optimization Applied to a Global Trajectory Optimization Problem

Troy A. Henderson and Daniele Mortari, Texas A&M University

A method of optimization based on rejection sampling (called the Learning Approach to Sampling Optimization) is presented for solving a global trajectory optimization problem. The given trajectory optimization problem was posed by ESA/ACT and has known solutions. The Learning Approach algorithm will be applied to the problem and the results are compared with the published solutions.

AAS 09 – 334

A Survey of Numerical Methods for Optimal Control

Anil V. Rao, University of Florida

A survey of numerical methods for optimal control is given. The objective of the article is to describe the major methods that have been developed over the years for solving general optimal control problems. In particular, the two broad classes of indirect and direct methods are discussed, the main approaches that are used in each class are described, and an extensive list is provided to relevant work in the open literature. Several important computational issues are then discussed and well known software programs for solving optimal control problems are described. Finally, a discussion is given on how to choose a method.

AAS 09 – 335

Method and Solution for the 2009 Global Trajectory Optimization Contest

Brianna S. Aubin, Bruce A. Conway, Jacob A. Englander, Alexander M. Ghosh, Christopher S. Martin, University of Illinois at Urbana-Champaign;
Bradley J. Wall, Embry-Riddle Aeronautical University at Prescott AZ

The 2009 Global Trajectory Optimization Contest challenged participants to design a trajectory leaving from the Earth and traveling to rendezvous with one near-Earth asteroid in a time frame of ten years, while intercepting as many asteroids as possible along the way. The spacecraft was specified as having an initial mass of 1500 kg, and an ion engine capable of providing 0.135 N of thrust with a specific impulse of 3000 s. The objective function J was the number of intermediate targets intercepted. The dual objective of maximizing the final mass of the spacecraft was to be used only in the event of a tie. In the solution presented here, a heuristic spiral method was invented and used to generate a near-feasible sequence of asteroids to visit. Then a direct transcription method was used to find the corresponding trajectory maximizing the spacecraft mass while ensuring satisfaction of the equations of motion, the initial constraints at the Earth, the intercept constraints at each intermediate target, and the rendezvous constraints at the final target. A sequence of 21 asteroids was found, with a final spacecraft mass of 524 kg.

AAS 09 – 337

Fast Sensitivity Computations for Trajectory Optimization

Nitin Arora, Ryan P. Russell, and Richard W. Vuduc, Georgia Institute of Technology

Gradient based trajectory optimization relies on accurate sensitivity information to robustly move a solution towards an optimum. Computational complexity of sensitivity calculations increases exponentially for higher problem dimensions and orders. Hence, the computation of these sensitivities is traditionally a major speed bottleneck in trajectory optimization and targeting algorithms. We propose to use Nvidia's GPU (Graphics Processing Unit) to rapidly calculate the derivatives in a multilayer, parallel, and heterogeneous way while the CPU (Central Processing Unit) sequentially computes the less expensive state equations. The proposed tool computes both the first and second order analytic sensitivities on the GPU with double precision accuracy. For an example trajectory propagation, we demonstrate overlapped computations such that sensitivities are calculated almost for free compared to the conventional CPU implementation.

AAS 09 – 338

New Approach to NLP-Based Trajectory Optimization of Space Applications

Sven O. Erb, ESA/ESTEC;
Andreas Wiegand and Sven Weikert, Astos Solutions GmbH

This paper presents a novel approach to NLP-based trajectory optimization through a dedicated NLP Solver development that is geared towards industrial space applications. eNLP has been developed as an all-modular solver that can be used as an IP-method with filters, or as an SQP-method with several solution schemes for the QP subproblem. An all-novel capability is the reverse communication feature for online user intervention. Apart from a general description of the concept behind eNLP, the paper also shows results for preliminary benchmark tests as well as for a set of application-driven trajectory optimization problems that were computed with an early version of eNLP.

AAS 09 – 339

On Ballistic Acquisition of Short Period Out-Of-Ecliptic Trajectories

Jun'ichiro Kawaguchi, Yasuhiro Kawakatsu, Mutsuko Morimoto, Japan Aerospace Exploration Agency (JAXA); Justin A. Atchison, Cornell University

This paper presents new orbital synthesis results to achieve ballistic and short period out-of ecliptic trajectories, instead of using electric propulsion or solar sail acceleration. The strategy developed utilizes a Jovian gravity first, followed by polar very high speed gravity assists by Earth or Venus. So far, the use of very high speed gravity assists has been conceived not practically useful. However, this paper presents those still effectively contribute to amending the trajectories periods, and to acquiring small sized out-of-ecliptic ballistic trajectories. The biggest advantage of this strategy is to reduce propellant mass carried drastically.

SESSION 6: ORBITAL DYNAMICS I
Chair: Dr. Matthew Berry, Analytical Graphics, Inc.

AAS 09 – 340
Vertical Correction of an Approximate Planar Periodic Orbit About the Larger Primary

Mohammed Ghazy and Brett Newman, Old Dominion University

In this paper, an approximate solution to the circular restricted three body problem, when the mass parameter is small and motion of third body is in the vicinity of the first primary, is subject to an analytic iterative correction process. The iterative scheme is based on adding small terms with order of magnitudes less than the base solution. These terms are obtained through solving differential equations with periodic coefficients using Floquet theory and a perturbation technique. The out of plane motion is found to be decoupled from the in plane motion and only exist under out of plane initial conditions excitation.

AAS 09 – 341
Improving Access to the Semi-Analytical Satellite Theory

Paul J. Cefola, Consultant in Aerospace Systems, Spaceflight Mechanics, and Astrodynamics; Donald Phillion and Ken S. Kim, Lawrence Livermore National Lab

The semi-analytical theory for the motion of a space object replaces the conventional equations of motion with two formulas: (1) equations of motion for the mean elements, and (2) expressions for the short periodic motion. Very complete force models have been developed for the mean element equations of motion and for the short periodic motion. There is also a semi-analytical theory for the partial derivatives of the perturbed motion. There is an interpolation strategy which greatly assists in producing the perturbed position and velocity and the partial derivatives at the output request times. The semi-analytical theory has been used extensively to study the long term evolution of orbits. The semi-analytical satellite theory has been interfaced with a variety of batch least squares and Kalman Filter estimation processes. The semi-analytical satellite theory software exists in two forms: as an option within the GTDS orbit determination system and as the Standalone Orbit Propagator Package. Both GTDS and the Standalone have been ported to the Linux environment. The Standalone also has been ported to the Windows environment. The current paper describes comparison tests between the Linux GTDS DSST, the Linux DSST Standalone, and the Windows DSST Standalone. A plan for a satellite theory distribution package is discussed. These tools also are being considered as a starting point for an open source software suite for Space Situational Awareness and space object catalog work. Linux GTDS already includes numerical, Semi-analytical, and the US NORAD GP orbit propagators: SGP, SGP4, HANDE, NAVSPASUR PPT2, and SALT. The addition to Linux GTDS of the US SGP8 and SDP8 satellite theories and the Russian A, AP, and NA satellite theories is being investigated.

AAS 09 – 342

Constraints on the Motion of Electrostatically Charged Spacecraft

Joseph W. Gangestad, George E. Pollock, James M. Longuski, Purdue University

Active modulation of the surface charge of a Lorentz spacecraft enables many capabilities—including inclination change, J_2 mitigation, and planetary escape—without propellant cost. We develop Lagrange's planetary equations with the Lorentz force and use these analytical expressions to explore the dynamics. Behavior discovered empirically in earlier studies follows directly from the planetary equations. For example, the small tilt of a magnetic dipole has a negligible effect on the orbit. We present a closed-form expression that constrains the set of equatorial orbits for which planetary escape is feasible, and identify a sufficient condition for escapability from inclined orbits.

AAS 09 – 343

Rock-Around Orbits

Scott Bourgeois and Daniele Mortari, Texas A&M University

The ability to observe specific orbits is a necessary requirement to perform space surveillance of resident space objects (RSOs). Using the theory of compatible orbits, this paper shows how to design specific repeating trajectories around assigned orbits. This unique orbit is called a "Rock-Around Orbit" (RAO) orbit, that will surround the assigned target orbit allowing the RAO satellite to perform 360 degree surveillance of any RSOs in the target orbit over a given period of time.

AAS 09 – 344

Keeping a Spacecraft on a Vertical Circular Orbit around an Earth-Moon Lagrange Point

Mohammed Ghazy and Brett Newman, Old Dominion University

A station keeping strategy for a spacecraft orbiting a collinear equilibrium point in the Earth-Moon system is introduced. A nominal circular solution which is derived from the Jacobi integral equation, employing elliptic integral theory, is used in a plane perpendicular to the line joining the two primaries. Thrust control inputs, which are found to be nonlinear functions of time, are used to negate the instability of the nominal orbit. Orbit parameters are chosen so that the cost of maintaining the nominal orbit is minimized. Analytical relationships for control requirements are developed.

AAS 09 – 345

Orbital Maneuvering with a Solar Sail through the Use of Natural Attitude Coning

Jay W. McMahon and Dale A. Lawrence, University of Colorado at Boulder

It has been shown that attitude equilibria exist in the LVLH frame for a solar sail under the influence of gravity gradient, aerodynamic, and solar torques. This paper explores the orbital effects of solar sails at and around these equilibria. It is shown that by moving the attitude in coning motions about the stable equilibria at orbital rates, nearly any orbital effect can be induced. Scaled results that can be easily applied to different sails or orbital conditions are derived. One possible application of modifying and/or stabilizing Sun-synchronous orbits is discussed in detail.

AAS 09 – 346

A New Navigation Force Model for Solar Radiation Pressure

Jay W. McMahon and Daniel J. Scheeres, University of Colorado at Boulder

This paper presents a new force model for solar radiation pressure acting on a satellite. The new model is based on a Fourier series representation of the satellite properties based on the position of the Sun with respect to the body. The perturbative effects on the satellite's orbit due to the solar radiation pressure are derived. This preliminary study shows that for a spacecraft in a circular orbit with synchronous rotation, the secular effect of solar radiation can be described with only seven Fourier coefficients. An example is discussed based on the GRACE satellite.

AAS 09 – 347

Solar Radiation Pressure Perturbations at Binary Asteroid Systems

Julie Bellerose and Hajime Yano, JAXA/JSPEC;
Daniel J. Scheeres, University of Colorado at Boulder

This paper analyses the solar influence at and within binary asteroid systems. Applications are for spacecraft missions in terms of both orbit dynamics and the evaluation of hazards due to dust. Natural phenomena are first discussed, such as sun interactions on the surface leading to dust levitation, which is especially important for small Near Earth asteroids and binary systems due to possible coupling with the binary dynamics. We then state mathematical expressions for analysis and go over basic methods and tools such as averaging to show the solar radiation pressure perturbations. Finally, we show simulations for current targets of interest, for both spacecraft and dust/particles applications.

SESSION 7: PLANETARY, ASTEROID AND DEEP SPACE MISSIONS I
Chair: Angela Bowes, NASA LaRC / Analytical Mechanics Associates

AAS 09 – 348

Accessing the Design Space for Solar Sails in the Earth-Moon System

Geoffrey G. Wawrzyniak and Kathleen C. Howell, Purdue University

Using a solar sail, a spacecraft orbit can be offset from a central body. Such a trajectory might be desirable for a single-spacecraft relay to support communications with an outpost at the lunar south pole. Although trajectory design within the context of the Earth-Moon restricted problem is advantageous, it is difficult to envision the design space for offset orbits. Numerical techniques to solve boundary-value problems can be employed to understand this new dynamical regime. Numerical finite-difference schemes are typically of low accuracy, but are simple to understand and implement. Two augmented finite-difference methods (AFDMs) are examined in a survey of different sail characteristics and initial guess strategies for the offset orbits. Strategies are presented that exploit knowledge from the AFDM solutions to yield more accurate results using other numerical tools.

AAS 09 – 349

Cassini-Huygens Maneuver Experience: First Year of the Equinox Mission

Emily M. Gist, Christopher G. Ballard, Yungsun Hahn, Paul W. Stumpf,
Sean V. Wagner, Powtawche N. Williams, Jet Propulsion Laboratory

The Cassini-Huygens spacecraft was launched in 1997 on a mission to observe Saturn and its many moons. After a seven-year cruise, it entered a Saturnian orbit for a four-year, prime mission. Due to the success of the prime mission, spacecraft health and remaining propellant, a two-year extended mission, the Equinox Mission, was approved. Maneuver designs and analyses performed through the first year of the Equinox Mission are presented. Results for the 43 most recent maneuvers are given. A substantial contribution to the navigation success of the Cassini-Huygens spacecraft is the continued accurate performance, exceeding the pre-launch expectations and requirements.

AAS 09 – 350

Flight Dynamics Operations for the IBEX Mission: The First Six Months

Lisa Policastri, John Carrico, Ryan Lebois, Applied Defense Solutions

As of August 1 2009, the Interstellar Boundary Explorer (IBEX) has completed its minimum six-month mission. This paper gives details of the flight dynamics operations for this first six months. The authors describe the specifics of how orbit determination is performed for this 7.5-day period cislunar trajectory with a 0.9 eccentricity. The methods used to calculate the orbit covariance, including predicted maneuvers, are described. The techniques used to handle the high eccentricity orbit are also described.

AAS 09 – 351

Overview of the Cassini Solstice Mission Trajectory

John Smith and Brent Buffington, Jet Propulsion Laboratory

The Cassini Project has completed a 7.2 year mission extension (1-Jul-2010 to 15-Sep-2017) which will govern the remainder of Cassini's operational lifetime. The resultant extended mission, stemming from 1.5 years of development, includes an additional 54 close Titan flybys, 12 close Enceladus flybys, 11 close flybys of other moons, and 160 orbits about Saturn in a variety of orientations. The mission ends with a spectacular series of orbits whose periapses are only a few thousand kilometers above Saturn's cloud tops culminating with impact into Saturn. This paper describes the different phases of the Solstice mission and the associated design methodology.

AAS 09 – 352

Astrodynamic Constraints on Mars Round-Trip Mission Design

Nicola Sarzi Amade' and James R. Wertz, Microcosm, Inc.

This paper presents in a mathematical form the basic constraints for interplanetary round trip travel. By starting from these general constraints, a more specific study of possible options for Mars round trip travels is presented. In particular, options at high energy and intermediate energy are discussed, which allow for rapid round trip missions. If the ΔV of a mission is increased enough, the total round trip time has a sudden drop in duration, that makes rapid round trips possible. Given a transfer time and a transfer arc, it is possible to determine the required arrival times. An "interplanetary train schedule" of transfer times to Mars can be constructed as a function of the available mission ΔV. The behavior of the constraints near transfer time singularities is presented.

SESSION 8: SPECIAL SESSION: OUTER PLANET FLAGSHIP MISSION
Chair: Nathan Strange, NASA / JPL

AAS 09 – 353

Europa Orbiter Mission Design with Io Gravity Assists

Kevin W. Kloster and James Longuski, Purdue University;
Anastassios E. Petropoulos, Jet Propulsion Laboratory

Recent improvements in radiation hardening enable spacecraft to endure greater radiation exposure than previously possible, in particular allowing the current iteration of the Europa Orbiter mission to perform several consecutive flybys of Io. The strategy for designing tours with Io flybys differs significantly from schemes developed for previous versions of the mission, but the Tisserand graph continues to provide important insights into the tour design. While Io flybys increase the duration of tours that are ultimately bound for Europa, they offer delta-v savings and greater scientific return, including the possibility of flying through the plume of one of Io's volcanoes.

AAS 09 – 354

Mission Design for the Jupiter Europa Orbiter Flagship Mission Study

Anastassios E. Petropoulos, Kevin W. Kloster and Damon F. Landau,
Jet Propulsion Laboratory

With high priority given to exploration of Europa in the National Research Council's last Planetary Science Decadal Survey, NASA commissioned the development of a mission concept for a flagship-class mission to Europa, which would include international collaboration, especially with an ESA Jupiter Ganymede Orbiter mission. Here we describe the Jupiter Europa Orbiter mission design. Numerous types of gravity-assist trajectories to Jupiter are analyzed, including a nominal 2020-launch, Venus-Earth-Earth trajectory. We also present a nominal Jovian system tour, whose purpose is not only study of the system, but also reduction of the size of the insertion burn into Europan orbit.

AAS 09 – 355

Broad Search for Solar Electric Propulsion Trajectories to Saturn with Gravity Assists

Try Lam, Damon Landau, and Nathan Strange, Jet Propulsion Laboratory

Solar electric propulsion (SEP) trajectories to Saturn using multiple gravity assists are explored for the joint NASA and ESA Titan Saturn System Mission concept. Results show that these new set of trajectories enable greater performance compared to chemical propulsion with similar gravity assists or SEP without gravity assists. This paper will discuss the method used in finding these interplanetary trajectories and examines variations in the performance for difference SEP systems, flight times, and flyby sequences. The benefits of the SEP trajectories for a mission to Saturn are also discussed.

AAS 09 – 356

Mission Design for the Titan Saturn System Mission Concept

Nathan Strange, Thomas Spilker, Damon Landau, Try Lam, Daniel Lyons,
Jet Propulsion Laboratory; Jose Guzman, Johns Hopkins Applied Physics Laboratory

In 2008, NASA and ESA commissioned a study of an international flagship-class mission to Titan, Saturn, and Enceladus consisting of a NASA orbiter and two ESA *in situ* elements, a Montgolfière hot air balloon and a lake lander. This paper provides an verview of the trajectory design for this mission, which consists of a solar electric in - terplanetary trajectory to Saturn, a gravity-assist tour of Titan and Enceladus, delivery of the two in situ elements, Titan aerobraking, and a Titan circular orbit.

AAS 09 – 357

An Overview of the Jupiter Europa Orbiter Concept's Europa Science Phase Orbit Design

Robert E. Lock, Jan M. Ludwinski, Anastassios E. Petropoulos, Karla B. Clark, and Robert T. Pappalardo, Jet Propulsion Laboratory

Jupiter Europa Orbiter (JEO), the proposed NASA element of the joint NASA-ESA Europa Jupiter System Mission (EJSM), could launch in February 2020 and conceivably arrive at Jupiter in December of 2025. The concept is to perform a multi-year study of Europa and the Jupiter system, including 30 months of Jupiter system science and a comprehensive Europa orbit phase of 9 months. This paper provides an overview of the JEO concept and describes the Europa Science phase orbit design and the related science priorities, model payload and operations scenarios needed to conduct the Europa Science phase. This overview is for planning and discussion purposes only.

AAS 09 – 358

Aerobraking at Titan

Daniel T. Lyons and Nathan J. Strange, Jet Propulsion Laboratory

NASA and ESA recently completed a Pre-Phase A concept study in support of a joint selection process for the next Outer Planet Flagship Mission. The following describes the aerobraking phase of the Titan Saturn System Mission concept. The mission would launch in 2020, require a solar electrically propelled, gravity assisted tour of the inner solar system before reaching Saturn 9 years later. The spacecraft would be propulsively captured into orbit around Saturn, where it would begin a two year, gravity assisted tour of the Saturnian system. A Montgolfière Balloon would be released at the first Titan flyby, while a lander would be released on the second Titan flyby. The spacecraft would be propulsively captured into a 19.7 hour orbit around Titan and immediately begin a two month aerobraking phase that would sample the atmosphere of the entire southern hemisphere. This paper describes the details of the aerobraking phase, which ends when the orbit is circularized at 1500 km to begin a 20 month science orbit phase.

AAS 09 – 359

Mission Design Issues for the European Orbiter of Laplace/EJSM: Callisto Flybys Sequence

Yves Langevin, CNRS and Université Paris Sud XI

The Laplace proposal has been pre-selected in 2008 for the "Large mission" slot in the Cosmic Vision program of ESA. The final selection will be announced in 2012. Laplace is now considered in the framework of a collaboration between ESA and NASA (EJSM), ESA being responsible for the JGO spacecraft primarily dedicated to the outer Galilean satellites (Ganymede and Callisto) while NASA will focus on the inner Galilean satellites (Io and Europa) with the JEO spacecraft. The ESA science definition team included in the science goals a comprehensive study of Callisto with a series of fly-bys before insertion in Ganymede orbit, so as to make possible a comparative study of these two satellites. The total accumulated radiation dose and the mass budget are critical design constraints for the JGO. Furthermore, the Callisto tour should not be detrimental to Ganymede science. Given the tidal lock of Callisto, illumination conditions are defined by the encounter position, while the terrains being overflown and the altitude of the fly-by are completely defined by the characteristics of the incoming and outgoing orbits. The proposed Callisto tours implement 180° transfers, with a relative velocity nearly perpendicular to the orbital plane. The optimum encounter velocity is therefore 2.05 to 2.1 km/s, as such a relative velocity can be rotated by 90° after two Callisto fly-bys at an altitude of 200 km or more. This contribution first demonstrates that it is possible to obtain these optimal encounter characteristics at a wide range of positions of Callisto on its orbit for any phasing configuration. We then show that returning to Ganymede with an optimum low encounter velocity is also possible for any phasing situation with an acceptable impact in time and ?V. This makes it possible to define an optimum Callisto tour without impacting the Ganymede orbiting phase as required by the science definition team. Strategies combining 180° transfers, 360° inclined transfers on 1:1, 2:3 and 2:1 resonant orbits and a few petal maneuver provides a wide variety of encounter positions with Callisto (hence illumination conditions) and excellent coverage with a mean interval of ~ 20 days between encounters (23 fly-bys for 443 days tour from Callisto arrival to Callisto departure. The proposed strategy makes it possible to target most regions of interests defined by the science definition team with favorable illumination conditions. Including 3:2 and 3:4 resonant orbits in the tour can provide a wider range of fly-by altitudes and near pericenter observations and an improved coverage of the inner and outer quadrants while increasing the tour duration.

SESSION 9: SPACECRAFT GUIDANCE, NAVIGATION AND CONTROL I
Chair: Kenneth Williams, KinetX, Inc.

AAS 09 – 360

Application of Time Varying Eigensystem Realization Algorithm to Guidance and Control Problems

Manoranjan Majji, Jer-Nan Juang, John L. Junkins, Texas A&M University

System identification method called the Time Varying Eigensystem Realization Algorithm is applied to input output simulated data of nonlinear system models. Resulting time varying model sequence is shown to approximate the first order departure motion dynamics about the nominal trajectory, leading to an effective model reduction procedure for nonlinear systems in discrete time. The time varying discrete time models thus obtained can be used for control and estimation purposes. The method is demonstrated on two representative problems in the present paper. First problem involves an optimal control problem involving the two dimensional motion of a point mass. It is conclusively demonstrated that in the presence of unstructured nonlinearities, using experimental (or simulated) data, models governing the departure motion dynamics can be explicitly constructed. These models are subsequently used in a perturbation guidance scheme. Subsequent example considers the dynamics of a point mass in a rotating tube apparatus. Models of the point mass are obtained from experimental data. Insights about the time varying coordinate systems are obtained by considering this physical example that naturally involves a time varying component.

AAS 09 – 361
Paper Withdrawn

AAS 09 – 362

Constrained, Minimum-Time Maneuvers for CMG Actuated Spacecraft

Andrew Fleming, Leffler Consulting, LLC;
Pooya Sekhavat and I. Michael Ross, U.S. Naval Postgraduate School

We address the time-optimal reorientation of a spacecraft with control moment gyros (CMGs) as the torque generating devices. The rigid-body solutions are inapplicable for a CMG-driven spacecraft due to the strong coupling between the actuator dynamics and the rigid-body equations. No assumptions are made with regards to the eigenaxis being the optimal axis for slewing. In sharp contrast to the rigid-body system, singular arcs occur quite naturally in the CMG-driven system. Solutions are computed using recent results from optimal control theory and pseudospectral methods. Our computed solutions are practically implementable in that we incorporate limits on the gimbal accelerations. The state space of the resulting optimal control problem is in R_{15}. Necessary conditions for this optimal control problem are derived and the extremality of the computed solution is demonstrated by way of Pontryagin's Principle. A key discovery of our analysis is the strong connection between CMG sizing and jerk limits.

AAS 09 – 363

Nonlinear Adaptive Control of a LEO Satellite Perturbed by Atmospheric Drag, J2 Effect, and Moon Gravity

Reza Raymond Karimi and Daniele Mortari, Texas A&M University

A nonlinear adaptive full state feedback linearization scheme was used to control the perturbed motion of a LEO spacecraft in a three-body problem. The perturbations were caused by atmospheric drag, J_2 effect, and the Moon gravitational field. The nominal trajectory of the spacecraft is known and the difference between the output of the system (current trajectory) and the nominal trajectory is the basis of designing of the controllers. Finally two scenarios were considered to validate the performance of the designed controllers.

AAS 09 – 364

Closed-Form Solution To the Minimum-Total-Delta-V-Squared Lambert's Problem

Jeremy Davis, Martín Avendaño and Daniele Mortari; Texas A&M University

A closed form solution to the Minimum-Total-Delta-V-Squared Lambert problem between two assigned positions in two general orbits is presented. Motivation comes from the need of computing optimal orbit transfer matrices for solving the re-configuration problem of satellite constellations and the complexity associated in facing this problem with the minimization of Total-Delta-V-Squared. The difference between a two-impulse Total-Delta-V-Squared and Total-Delta-V orbit transfer is bounded. The solving equation of Minimum-Total-Delta-V-Squared Lambert problem is a quartic polynomial in term of the angular momentum modulus of the optimal transfer orbit. Root selection is discussed and the singular case, occurring when the initial and final radii are parallel, is analytically solved. One numerical example is given for the general case (transfer between no-coplanar elliptical orbits).

AAS 09 – 365

Comparison between the Mission Design and Reconstruction of the Cassini-Huygens Trajectories and Maneuvers of the Prime Mission

P. W. Stumpf, C.G. Ballard, E. M. Gist, Y. Hahn, J. B. Jones, S. V. Wagner, and P. N. Williams, Jet Propulsion Laboratory

During the Cassini-Huygens orbital phase, the maneuver team collected data to determine the maneuver prediction accuracy and maneuver implementation accuracy as well as data to assess the ability of the navigation team to adhere to the reference trajectory. During the mission planning stage, questions arose as to what level the spacecraft would be able to maintain the reference trajectory and what value of statistical maneuver cost would be needed for each encounter. Conservative answers were provided due to the lack of similar data from past projects. Data obtained by the maneuver team and analysis that revisits these questions is presented.

AAS 09 – 366

Continuous-Time Bilinear System Identification Using Repeated Experiments

Manoranjan Majji, Jer-Nan Juang, John L. Junkins, Texas A&M University

A novel method is presented for the identification of continuous time bilinear system models, from the input output data associated with multiple experiments. Making use of the recent advances in bilinear system identification, the current work documents the advantage of utilizing multiple experiments and sets up a procedure to obtain bilinear system models. It is shown that the special pulse inputs employed by earlier research can be avoided and accurate identification of the continuous time system model is possible by performing multiple experiments incorporating a class of control input sequences. The algorithm presented here-in is more attractive in practice for the identification of bilinear systems. Numerical examples presented demonstrate the methodology developed in the paper.

AAS 09 – 367

On Underweighting Lidar Measurements

Renato Zanetti, The Charles Stark Draper Laboratory;
Kyle J. DeMars and Robert H. Bishop, The University of Texas at Austin

Underweighting is an *ad hoc* technique to reduce the Kalman filter update in order to compensate for unaccounted second order terms in the Taylor series expansion of the filter's residual. Existing underweighting techniques are revisited, these techniques heavily rely on trial and error to finalize the design. For the case of underweighting lidar measurements, a new scheme is introduced to aid the tuning of the filter, obtaining a viable underweighting coefficient bounding the second order terms.

SESSION 10: CONJUNCTION ASSESSMENT I
Chair: Robert Hall, AGI

AAS 09 – 368

Analysis of the Iridium 33-Cosmos 2251 Collision

T. S. Kelso, Center for Space Standards & Innovation (CSSI)

On 2009 February 10, Iridium 33—an operational US communications satellite in low-Earth orbit—was struck and destroyed by Cosmos 2251—a long-defunct Russian communications satellite. This is the first time since the dawn of the Space Age that two satellites have collided in orbit. To better understand the circumstances of this event and the ramifications for avoiding similar events in the future, this paper provides a detailed analysis of the predictions leading up to the collision, using various data sources, and looks in detail at the collision, the evolution of the debris clouds, and the long-term implications for satellite operations.

AAS 09 – 369

It's Not a Big Sky after All: Justification for a Close Approach Prediction and Risk Assessment Process

Lauri Kraft Newman, NASA Goddard Space Flight Center;
Ryan Frigm and David McKinley, a.i. solutions, Inc.

There is often skepticism about the need for Conjunction Assessment from mission operators that invest in the "big sky theory", which states that the likelihood of a collision is so small that it can be neglected. On 10 February 2009, the collision between Iridium 33 and COSMOS 2251 provided an indication that this theory is becoming invalid and that a CA process should be considered for all missions. This paper presents statistics of the effect of the Iridium/COSMOS collision on NASA's Earth Science Constellation as well as results of analyses which characterize the debris environment for NASA's robotic missions.

AAS 09 – 370

A First Order Forensic Analysis of the Iridium 33 / Cosmos 2251 Collision

Johannes M. Hacker, Emergent Space Technologies, Inc.

Several recent breakup events have significantly worsened the orbital debris environment in low earth orbit (LEO). China's anti-satellite (ASAT) test of January 2007, in which the Chinese military destroyed a decommissioned weather satellite called Fengyun-1C (FY-1C) generated an additional 2378 objects in the Space Surveillance Network (SSN) catalog. As of July 31, 2009 an additional 1263 pieces of debris have been added to the SSN catalog due to the collision of Iridium 33 and Cosmos 2251 on February 10, 2009. 895 of these pieces are from Cosmos 2251 and 368 are from Iridium 33. It took just over a year for the SSN to add all of the current FY-1C debris pieces to the catalog. Satellite breakups due to explosions have been modeled based upon empirical data in the past. But empirical data on breakups caused by hypervelocity impact have only become available due to recent unfortunate events. A first order forensic reconstruction of the Iridium 33 / Cosmos 2251 collision similar to one conducted on FY-1C is presented. This reconstruction is based upon backward propagation of TLE's to the impact point, and generating a three dimensional velocity distribution of the debris pieces. This backward propagation was a simple analytic propagation which considered only a J_2 gravity model and accounted for atmospheric drag by assuming a linear change in semi-major axis and eccentricity. The orbit propagation and velocity distribution calculation will be done using MATLAB and the STK Connect tool. Once generated, these velocity distributions and subsequent debris cloud propagation can be visualized using STK's Visualization Option.

AAS 09 – 371

Correlating Spacecraft Debris from Various Tracking Measurements

Timothy A. Craychee and John P. Carrico, Applied Defense Solutions;
Richard Hujsak Analytical Graphics Inc.

The collision of Iridium 33 and Cosmos 2251 is just one example that demonstrated a difficult problem in tracking space objects: correlating the debris created by the impact of various tracking measurements. While it may be possible to discern how many pieces of debris were created, consistently identifying each individual piece from one set of tracking data to the next is a long and complex problem. The purpose of this paper is to demonstrate an alternate method of correlating tracking data to the individual pieces of debris, and to generate a high precision position and velocity for each piece. This correlated data can then be used in an orbit determination tool to determine and predict the orbit of the various pieces of debris.

AAS 09 – 372

A Description of Filters for Minimizing the Time Required for Orbital Conjunction Computations

James Woodburn, Vincent Coppola and Frank Stoner, Analytical Graphics, Inc.

Classical filters used in the identification of orbital conjunctions are described and examined for potential failure cases. Alternative implementations of the filters are described which maintain the spirit of the original concepts but improve robustness. The computational advantage provided by each filter when applied to the one versus all and the all versus all orbital conjunction problems are presented. All of the classic filters are shown to be applicable to conjunction detection based on tabulated ephemerides in addition to two line element sets.

AAS 09 – 373

A Single Conjunction Risk Assessment Metric: The F-value

Ryan Clayton Frigm, a.i. solutions Inc.

The Conjunction Assessment Team at NASA Goddard Space Flight Center provides conjunction risk assessment for many NASA robotic missions. These risk assessments are based on several figures of merit, such as miss distance, probability of collision, and orbit determination solution quality. However, these individual metrics do not singly capture the overall risk associated with a conjunction, making it difficult for someone without this complete understanding to take action, such as an avoidance maneuver. The goal of this analysis is to introduce a single risk index metric that can easily convey the level of risk without all the technical details. The proposed index is called the conjunction “F-value.” This paper presents the concept of the F-value and the tuning of the metric for use in routine Conjunction Assessment operations.

AAS 09 – 374

Assessing Satellite Conjunctions for the Entire Space Catalog using COTS Multi-core Processor Hardware

Vincent T. Coppola, Sylvain Dupont, Kevin Ring and Frank Stoner,
Analytical Graphics Inc.

The recent collision of the Iridium 33 spacecraft with Cosmos 2251 debris has shown the importance of conducting conjunction assessments on a continual regular basis for operational spacecraft. We study the feasibility of assessing the entire space object catalog (i.e., all-on-all assessment) for 1 and 5 day analysis periods, using both low and high fidelity ephemerides, using COTS software and COTS multi-core processor hardware. We show that a catalog of 12,000 space objects (involving almost 72 million pairings) can be assessed within one hour and thus incorporated into an operational environment. The impact on the assessment of larger catalogs (e.g., 20K or 100K objects) will also be discussed.

AAS 09 – 375

The Collision Risk Assessment and Risk Mitigation Process for the NPP and NPOESS Missions

Amy Bleich, General Dynamics, Inc.;
Matthew Duncan and Josh Wysack, a.i. solutions, Inc.

Orbital debris poses a significant threat to spacecraft health and safety. The current estimate of the number of 'tracked' objects that are larger than 10 cm is estimated at approximately 20,000. Most of these tracked objects are characterized as orbital debris. Satellites are routinely hit by small particles that cause little or no damage. However, if a large particle were to hit an operational satellite, the impact could result in the end of the mission. A large part of the orbital debris population resides in low earth orbit (LEO), where the density distribution of cataloged objects is concentrated near mean equatorial altitudes of 700 – 1100 km. Because of the ever increasing threat posed by orbiting objects, the National Polar-Orbiting Operational Environmental Satellite System (NPOESS) Program Office has established a risk assessment and risk mitigation process for the NPOESS satellite constellation. This process consists of daily analysis of close approach data produced by the United States Strategic Command's (USSTRATCOM) Joint Functional Component Command for Space (JFCC-Space) through its 24/7 operations center, the Joint Space Operations Center (JSpOC). This document describes the collision risk assessment operations concept that will be employed for the NPOESS project. The NPOESS program is managed by a tri-agency Integrated Program Office (IPO), involving personnel from the Department of Commerce (DoC), Department of Defense (DoD) and the National Aeronautics and Space Administration (NASA).

SESSION 11: TRAJECTORY OPTIMIZATION II
Chair: Dr. Anastassios Petropoulos, Jet Propulsion Laboratory

AAS 09 – 376
Lunar Orbit Insertion from a Fixed Free Return

Mark C. Jesick and Cesar A. Ocampo, The University of Texas at Austin;
Gerald L. Condon, NASA Johnson Space Center

In support of NASA's Constellation program that will return humans to the moon, the present research combines lunar free return trajectories with lunar orbit insertion (LOI) sequences to provide both crew safety and selenographic versatility. Because future missions necessitate global lunar access, the required spacecraft plane change at the moon may be large enough that a multi-maneuver sequence offers velocity impulse cost savings. This paper develops a targeting and optimization procedure to transfer a spacecraft from a lunar free return trajectory to a closed lunar orbit through a multi-maneuver LOI sequence. Thus, a safe earth-return for crew is guaranteed while not compromising the ability to achieve any lunar orbit.

AAS 09 – 377
Shrinking the V-infinity Sphere: Endgame Strategies for Planetary Moon Orbiters

Ryan C. Woolley and Daniel J. Scheeres, University of Colorado

Delivering an orbiter to a planetary moon such as Europa or Titan requires an excessive amount of fuel if the trajectory is not carefully and cleverly planned. Investigations of endgame strategies such as V-infinity leveraging in conjunction with resonant orbits have shown promising results. Making use of a new graphical technique, it is possible to better visualize the optimal use of V-infinity leveraging maneuvers and fly-bys to reduce hyperbolic excess velocity and ultimately capture into orbit. Initial numerical results show that the optimal location for performing V-infinity reduction maneuvers is not necessarily at apoapsis, due to targeting constraints.

AAS 09 – 378
A Collocation Approach for Computing Solar Sail Pole-Sitter Orbits

Martin T. Ozimek, Daniel J. Grebow and Kathleen C. Howell, Purdue University

Implementation of a 12th-order Gauss-Lobatto collocation scheme is detailed, including mesh refinement iterations to meet a user-specified error tolerance. The algorithm is robust and efficient, locating path constrained orbits when little information is available regarding the behavior of the solutions. Using a Fourier series control law, the method is applied to the computation of highly unstable, pole-sitter orbits in the Earth-moon restricted three-body problem. The results are comparable to those obtained with standard explicit propagators.

AAS 09 – 379

Kepler Trajectory Design

Roby S. Wilson, Julie A. Kangas and Min-Kun J. Chung, Jet Propulsion Laboratory

The Kepler mission launched on March 6, 2009, placing the spacecraft in an Earth-trailing heliocentric orbit. The primary objective of the Kepler mission is to better understand the origins of the Solar System by determining the frequency of Earth-like planets around other stars. The Kepler science instrument itself is a highly sensitive photometer that will conduct a census of extra-solar terrestrial planets by observing the dimming of light caused by planetary transits in a fixed portion of the sky. This paper will provide a brief overview of the mission and then describe in detail the design of the Earth-trailing trajectory to support this planet finding survey.

AAS 09 – 380

Global Performance Characterization of the Three Burn Trans-Earth Injection Maneuver Sequence over the Lunar Nodal Cycle

Jacob Williams and Elizabeth C. Davis, Engineering and Science Contract Group;
David E. Lee, Gerald L. Condon and Timothy F. Dawn, NASA Johnson Space Center;
Min Qu, Analytical Mechanics Associates, Inc.

The Orion spacecraft will be required to perform a three-burn trans-Earth injection (TEI) maneuver sequence to return to Earth from low lunar orbit. The origin of this approach lies in the Constellation Program requirements for access to any lunar landing site location combined with anytime lunar departure. This paper documents the development of optimized databases used to rapidly model the performance requirements of the TEI three-burn sequence for an extremely large number of mission cases. It also discusses performance results for lunar departures covering a complete 18.6 year lunar nodal cycle as well as general characteristics of the optimized three-burn TEI sequence.

AAS 09 – 381

Variational Model for the Optimization of Constrained Finite-Burn Escape Sequences

Cesar Ocampo and Jean-Philippe Munoz, University of Texas at Austin

This paper presents the derivation of the variational equations associated with a one or three-finite burn escape sequence from a lunar parking orbit to a hyperbolic trajectory. The variational equations are obtained via a general method, using the state-transition matrix associated with an augmented state-vector that contains the position, velocity and mass of the spacecraft, the thrust magnitude and direction, and the exhaust velocity. These equations allow one to compute the gradients required to optimize the cost of the escape transfer using a Sequential Quadratic Program.

AAS 09 – 382

Preliminary Trajectory Design for the Artemis Lunar Mission

Stephen B. Broschart, Min-Kun J. Chung, Sara J. Hatch, Jin H. Ma,
Theodore H. Sweetser and Stacy S. Weinstein-Weiss, Jet Propulsion Laboratory;
Vassilis Angelopoulos, UCLA

The ARTEMIS mission is an extension to the THEMIS mission that will send two of the Earth-orbiting THEMIS probes on a circuitous route to the Moon beginning in July 2009. This paper describes the ARTEMIS trajectory designs proposed to the NASA Senior Review in April 2008 (and accepted in May 2008). The trajectory design is very challenging due to the constraints imposed by the capabilities of the orbiting hardware. Nonetheless, the mission science objectives are successfully addressed by two unique trajectory solutions which include multiple lunar approaches, lunar flybys, low-energy trajectory segments, lunar Lissajous orbits, and low-lunar orbits.

SESSION 12: ATTITUDE DYNAMICS, DETERMINATION AND CONTROL II
Chair: William Cerven, The Aerospace Corporation

AAS 09 – 383
Paper Withdrawn

AAS 09 – 384

Low-Cost Approaches to Star Tracker Lab Testing

Tom Dzamba and John Enright, Ryerson University

This study presents a method of star simulation for microsatellite star trackers that allows for a dynamic laboratory setup. Common setups for this application involve labourous measurement and positioning of components making the lab environment inflexible and the task of testing numerous sensors lengthy. The proposed method minimizes this need of manual setup through the use of a self-calibrating project-screen-sensor system. A general analytical model and a projected calibration pattern are utilized to determine a set of parameters that define all nonidealities in the lab setup. These parameters are then used to project deformed images that, when imaged by the star tracker, appear as desired. The entire procedure takes approximately 25min and results in a mean angular star placement accuracy of 0:0073º. Although the mean error is comparable to other common forms of star simulation, there is still room for improvement. Future work still needs to be done to address some remaining regions of increased angular error at the extents of the FOV and around the sensor boersight.

AAS 09 – 385

Information Theoretic Weighting for Robust Star Centroiding

Brien R. Flewelling and Daniele Mortari, Texas A&M University

A statistical methodology for the global and local analysis of star tracker image content is presented which is based on the A-Contrario framework. A level set analysis using this methodology effectively weights signals with a confidence interval based on the information content. Globally this analysis can represent the non-planar noise floor associated with the sky background. Locally, this analysis can automatically define the annulus which represents the partial pixels associated with the boundary between signal and noise. The performance of centroiding with information theoretic weighting is evaluated compared to traditional thresholding methods for simulated and real star tracker images.

AAS 09 – 386

On the Relationships between Proofs of Convergence in Continuous and Discrete Time Iterative Learning Control

Joe W. Yeol and Richard W. Longman, Columbia University;
Hans Georg Bock, University of Heidelberg, Germany

Iterative learning control (ILC) aims to produce zero tracking error in a control system that performs the same task repeatedly. This is done by adjusting the command input each run, based on the error history observed in the previous run. There are spacecraft applications for scanning maneuvers of sensors. Much of the control literature uses continuous time models and develops proofs of convergence using a *lambda*-norm, establishing that there exists a value of *lambda* that creates monotonic decay of this norm of the error. This paper aims to build bridges between these continuous time methods for nonlinear systems to the proofs of convergence for linear discrete time systems. The continuous time proof is modified to deal with nonlinear difference equations and with nonlinear differential equations fed by a zero order hold. The convergence is monotonic in the *lambda*-norm of the error, but simulations of the Euclidean norm can exhibit exponential overflow and still have monotonic decay in this norm. Material is presented to show how this can happen. One would like monotonic decay of the Euclidean norm of the error, and it is shown that this can always be accomplished by use of a sufficiently small learning gain or by use of a sufficiently long sample time interval. It is likely that what is required is too extreme for practical applications, and in order to make the learning law practical one needs to use a zero-phase low-pass filter cutoff of the learning.

AAS 09 – 387

Identification of Linear Time-Varying Systems By a Canonical Representation

Minh Q. Phan, Dartmouth College; Richard W. Longman, Columbia University;
Jer-Nan Juang, National Cheng-Kung University

This paper presents a method to identify time-varying state-space models by canonical representation. Unlike recent OKID/ERA based methods which work through the observer Markov parameters, this method uses the canonical forms to derive the time-varying state-space models. The paper describes the relationship between a time-varying state-space model and a time-varying auto-regressive moving-average (ARX) model and various canonical forms that convert a time-varying ARX model to a time-varying state-space model. Numerical examples are provided to illustrate the developed identification method.

AAS 09 – 388

Sliding Mode Observer for Spacecraft Attitude Estimation: A Special Case

Mohamed M. Aly, Old Dominion University;
Hossam Eldin-A. Abdel Fatah and Ahmed Bahgat, Cairo University

This paper presents a sliding mode observer (SMO), that can be used for moderate-accuracy attitude determination systems for LEO Earth-pointing spacecraft (s/c), which is typically using Gyroscopes, Earth, and Sun sensors for attitude sensing, this is to provide a substitute for the yaw data in case of the s/c eclipse periods or limited field of views. The nonlinear observability for this system is investigated analytically via the calculation of Lie derivatives to check the possibility of the system states estimation. The performance of the SMO observer is presented, the stability for the SMO is proven and SMO enhanced estimates is shown.

SESSION 13: FORMATION FLYING
Chair: Brian Gunter, Delft University of Technology

AAS 09 – 389

Charged Spacecraft Formations: A Trade Study on Coulomb and Lorentz Forces

George E. Pollock, Joseph W. Gangestad and James M. Longuski, Purdue University

Electrostatically charged spacecraft have been proposed for formation flying applications in LEO and GEO. The inter-spacecraft Coulomb force acts internally to the formation, while the geomagnetic Lorentz force provides an external perturbation. A relative motion dynamical model is developed that includes the effect of both Coulomb and Lorentz forces. The Debye length is modeled as a function of altitude, and a domain of altitudes and separation distances is identified where both forces have similar magnitudes. Given advances in technology and in space plasma knowledge, notional Coulomb-Lorentz spacecraft formations are introduced that use electromagnetic forces alternatively for formation control and orbit control.

AAS 09 – 390

Closed-Loop One-Dimensional Charged Relative Motion Experiments Simulating Constrained Orbital Motion

Carl R. Seubert and Hanspeter Schaub, University of Colorado

Coulomb spacecraft actively control their potential through continuous charge emission to generate inter-spacecraft electrostatic forces. Modeling the complex induced charge effects and coupling with the plasma environment is very challenging. This paper presents charged relative motion experiments demonstrating how active charge feedback control tests can be performed in a terrestrial environment without resorting to expensive vacuum or plasma chambers. The non-conducting test bed is able to levitate a conducting sphere with only milli-Newton level disturbance forces. The relative motion is achieved by having one charged sphere stationary and one charged sphere floating on the track. Charge control is provided through an external potential source connected to the spheres through a small conducting wire. The one-dimensional (1-D) test track can mimic the constrained motion along the orbit radial, along-track, or out-of-plane direction. These dynamical systems are replicated with the test track by either leveling it, or adding a small tilt to bias the relative motion in one direction. Experimental results illustrate the performance of a simple charge feedback control for these orbital scenarios.

AAS 09 – 391

Switched Lyapunov Function Based Coulomb Control of a Triangular 3-Vehicle Cluster

Shuquan Wang and Hanspeter Schaub, University of Colorado

This paper studies a three-body Coulomb virtual structure control problem. For a formation of three spacecraft flying freely in deep space, actively controlled Coulomb forces are used to stabilize the formation shape to a desired triangular configuration. The control problem is challenging because the system is nonlinear and nonaffine, while the direct control of all three sides at the same time is often not implementable using only real charges. Firstly, a two-side switched control strategy is developed to control the two sides with the worst shape errors such that the implementable charge control solution is guaranteed. However, analytical and practical stability issues arise due to the discrete control time steps. Using the multiple Lyapunov functions analysis tool, a stable switched control strategy is setup in a manner such that the activated error function is decreasing rapidly enough to compensate for a potentially increased amount during the last uncontrolled control cycle. Thus all the error functions are made *Lyapunov-like* and the global stability of the switched control strategy is guaranteed. Perfect convergence to desired triangular shape is not physically achievable with Coulomb forces alone because the triangle is not a natural equilibrium solution. Numerical simulations illustrate the effectiveness of the stable switched control strategy.

AAS 09 – 392

A Peer-to-Peer Refueling Strategy using Low-thrust Propulsion

Atri Dutta, Nitin Arora and Ryan P. Russell, Georgia Institute of Technology

The problem of minimum-fuel, time-fixed, low-thrust rendezvous is addressed with the particular aim of developing a solver to determine optimal low-thrust Peer-to-Peer (P2P) maneuvers, which will be an integral part of distributed low-thrust servicing missions for multiple satellites. We develop the solver based on an indirect optimization technique and utilize the well-known shooting method to solve the two-point boundary value problems associated with the forward and return trips of a P2P maneuver. We finally demonstrate the application of the tool in determination of the optimal P2P maneuvers required for a low-thrust P2P mission for multiple satellites moving in a circular orbit. The development of this solver is a first step in the direction of studying low-thrust servicing missions for multiple satellites in circular constellations.

AAS 09 – 393

Nonlinear Coulomb Feedback Control of a Spinning Two Spacecraft Virtual Structure

Shuquan Wang and Hanspeter Schaub, University of Colorado at Boulder.

This paper studies a spinning two-spacecraft Coulomb virtual structure control problem in an orbital environment. Only Coulomb forces are utilized to control the configuration of the two-spacecraft formation flying in a geostationary orbit. After deriving the separation distance equation of motion, a feed-forward nominal control charge is developed by assuming purely two spacecraft configuration. An asymptotically stable full-state feedback control is developed. It requires the inertial and relative position vectors which are difficult to measure accurately. A partial-state feedback control is proved stable assuming a fast spinning rate thus the influence of the orbital motion can be neglected. The boundaries of the orbital motion part are proved to be neglectable for a tight formation in a geostationary orbit. An integral feedback term can be utilized to compensate for the error in estimating the feed-forward nominal charge product but the stability is not proved. Numerical simulations illustrate the performance of the controllers.

AAS 09 – 394

RF Based Navigation for PRISMA and Other Formation Flying Missions in Earth Orbit

Michel Delpech, Pierre-Yves Guidotti, Thomas Grelier and Jon Harr,
Centre National d'Etudes Spatiales

A navigation system based on a new Radio Frequency sensor for relative positioning of satellites in formation has been developed for the PRISMA demonstration mission to be launched at the end of 2009 in LEO. Navigation relies on an Extended Kalman Filter that includes an accurate modeling of relative dynamics and performs measurement biases estimation. Results obtained during the extensive ground validation show the satisfactory behavior of the filter in presence of measurement biases and acceleration errors due to maneuvers. The paper evokes how this function can still be applicable for future missions like Proba3 that fly on very elliptical orbits and what level of performances can be achieved.

AAS 09 – 420

Formation Flying Control Implementation for Highly Elliptical Orbits

Pedro A. Capó-Lugo, NASA Marshall Space Flight Center;
Peter M. Bainum, Howard University

The Tschauner-Hempel equations are used to correct the separation distance drifts between a pair of satellites within a constellation in highly elliptical orbits. This set of equations was discretized in the true anomaly angle to be used in a digital steady-state hierarchical controller. The objective of a discretized system is to develop a simple algorithm to be implemented in the computer onboard the satellite. The main advantage of discrete systems is that the computational time can be reduced by selecting a suitable sampling interval. The purpose of this paper is to show an implementation of the discrete Tschauner-Hempel equations and the steady-state hierarchical controller in the computer onboard the satellite. This set of equations is expressed in the true anomaly angle in which a relation between the time and the true anomaly angle domains is formulated.

SESSION 14:
DYNAMICAL SYSTEMS THEORY APPLIED TO SPACE FLIGHT
Chair: Dr. Kathleen Howell, Purdue University

AAS 09 – 395
KAM Tori Normal Coordinates

William E. Wiesel, Air Force Institute of Technology

The solution to motion in the vicinity of a KAM torus is constructed. Applying both the KAM theorem and assuming that Hamiltonian motion holds on at least a Cantor set of adjacent tori, the local linearization of a KAM torus can be constructed. A set of eigenvalue–like quantities must be determined to produce a description of local motion that remains bounded. The local motion near a KAM torus involves linear drift, and the Jordan form needs to be generalized to a full symmetric matrix.

AAS 09 – 396
Instability Characterization of Spacecrafts Near Stable Manifolds

Iman Alizadeh and Benjamin Villac, University of California, Irvine

Recent endeavors in space exploration of the outer system raised new stability questions for the motion of spacecraft in strongly perturbed environments. Although stable manifolds provide thrust free transfers between distant regions in phase space, the natural stability around these trajectories has not been investigated systematically. In this paper the notion of recovery time around stable manifolds is analyzed to characterize stability around stable manifolds. A semi-analytical approach to determine the most unstable direction which corresponds to the minimum recovery time along the stable manifolds is presented and its relation to the Lyapunov vectors is investigated. Once this direction is available, a robust boundary around the stable manifolds can be constructed such that, as long as the spacecraft coasts within this boundary, the missed distance between the spacecraft and the target equilibrium point/periodic orbit will be less than the desired value. The results obtained show significant computational reduction for stability analysis of trajectories in unstable orbital environments. Apart from planetary protection requirements, the results can also be applied for spacecraft rendezvous and docking operations as long as one of the spacecrafts flies near an unstable equilibrium point or an unstable periodic orbit.

AAS 09 – 397

Numerical Exploration of Small-Body Orbiter Dynamics Using Chaoticity Indicators

Benjamin F. Villac and Katherine Yi-Yin Liu, University of California, Irvine;
Stephen B. Broschart, Jet Propulsion Laboratory

Previous research indicated the feasibility and usefulness of chaoticity indicator maps to analyze the complex dynamics associated with realistic small body orbiters models. This paper explores further this method by exploring different indicators, such as orthogonal FLI, mean FLI and other sensitivity indicators to reveal additional dynamical structure (such as invariant manifolds and periodic orbits) that are relevant to spacecraft mission trajectory design. This study allows us to better characterize the size of the stability region in state space and use such information in a mission design context.

AAS 09 – 398

Locally Optimal Transfers between Libration Point Orbits Using Invariant Manifolds

Kathryn E. Davis, Rodney L. Anderson, Daniel J. Scheeres and George H. Born, University of Colorado

A method is developed for constructing locally optimal transfer trajectories between libration point orbits with different energies. The unstable manifold of the first orbit is connected to the stable manifold of the second orbit by the execution of two or more maneuvers. Two-body parameters define the selection of the unstable and stable manifold trajectories used for the transfer. The maneuver locations along the manifolds are determined by an application of primer vector theory. This method produces fuel costs up to 73% less than transfers trajectories that do not employ the use of manifolds.

AAS 09 – 399

Transfers to Periodic Distant Retrograde Orbits

Christopher J. Scott and David B. Spencer, The Pennsylvania State University

The existence of collision orbits in the vicinity of the distant retrograde region is well-documented in works involving satellite capture. This study utilizes the orderly arrangement of collision regions and a simple dynamical analysis to facilitate a focused sampling of phase space. This limited sampling provides an accurate guess for differential correction and numerical continuation algorithms for an arbitrary number of transfer types. A procedure is outlined that calculates favorable insertion points in terms of transfer time and delta-V. The relationship between families of transfer orbits and the morphology of phase space near the distant retrograde region is discussed.

AAS 09 – 400

Transfers to Sticky Distant Retrograde Orbits

Christopher J. Scott and David B. Spencer, The Pennsylvania State University

This study extends techniques developed in a previous study to single impulse transfers and transfers to quasi-periodic orbits. A single impulse transfer takes the spacecraft to the fringes of the stability region where it can reside for an extended period of time in a sticky orbit. These transfers are useful for spacecraft with no propulsive mechanism. The latter involves insertion into a sticky orbit before stabilizing maneuver into a quasi-periodic orbit within the stable distant retrograde region. These transfers have the benefit of delayed escape from the Earth region and fuel savings over comparable transfers to the central periodic orbit.

AAS 09 – 402

New Families of Multi-Revolution Terminator Orbits Near Small Bodies

Stephen B. Broschart, Jet Propulsion Laboratory; Daniel J. Scheeres, University of Colorado at Boulder; Benjamin F. Villac, University of California at Irvine

Terminator orbits are known to be robust under the influence of a large solar radiation pressure perturbation and a weak and irregular gravitational potential. These orbits are ideal for missions that require long-term stable motion near small asteroids and comets. This paper describes the geometry and stability characteristics of two examples of a new class of multi-revolution terminator orbits. These orbits offer improved observation geometry for some scientific observations over terminator orbits while retaining long-term stability and robustness characteristics.

SESSION 15: SPACECRAFT GUIDANCE, NAVIGATION AND CONTROL II

Chair: Dr. Peter Lai, The Aerospace Corporation

AAS 09 – 403

Failure-Robust Thruster Commanding for Space Vehicles Control

Fabio Curti, Sapienza University of Rome;
Riccardo Bevilacqua and Marcello Romano, Naval Postgraduate School

In this paper we study the problem of controlling dynamics of a spacecraft by on-off thrusters only in the case of actuators' failures. We assume that one or more thrusters can fail and that the logic driving the translational and rotational dynamics does not have any information on these events. In particular, the methodology guarantees the Lyapunov-stable tracking of linear models for both the translational and the rotational dynamics of the spacecraft.

AAS 09 – 404

Nonlinear Monte Carlo Mission Simulation and Statistical Analysis

Christopher L. Potts, Richard M. Kelly and Troy D. Goodson,
Jet Propulsion Laboratory

Monte Carlo mission simulations combine *a priori* and predicted knowledge uncertainties, flight path control strategies, error models, trajectory sensitivities, and ground design schedules to evaluate and enhance mission system performance. Nonlinear modeling capabilities are required to support advanced mission types that include low-thrust, orbiter mapping, low-energy or third body trajectory variation, and Lissajous orbits. FARO is a prototype software system that provides nonlinear Monte Carlo mission simulation and continuous statistical analysis capabilities with a multi-mission architecture that supports both low- and high-thrust propulsion. The prototype system is being used to investigate sensitivities and operation planning for the Dawn and Grail missions.

AAS 09 – 405

Pseudospectral Optimal Control on Arbitrary Grids

Qi Gong, University of California, Santa Cruz;
I. Michael Ross and Fariba Fahroo, Naval Postgraduate School

In advancing our prior work on a unified theory for pseudospectral (PS) optimal control, we present new results for PS methods over arbitrary grids. These results provide a way to compare performances among different PS methods and suggest guidelines to choose the proper grids and discretization approaches for solving optimal control problems. The new unified ideas reveal hidden properties of different types of PS methods and pave the way to construct more efficient algorithms for solving different types of optimal control problems. Our computational framework is not based on any particular choice of orthogonal polynomials; therefore, the approach unifies Legendre and Chebyshev PS methods under one framework.

AAS 09 – 406

Simultaneous Computation of Optimal Controls and their Sensitivities

Chris M. McCrate and Srinivas R. Vadali, Texas A&M University

This paper presents a method for solving a class of fixed-time optimal control problems for non-linear dynamical systems. The method focuses on obtaining an approximate solution to the Hamilton-Jacobi-Bellman (HJB) partial differential equation, valid at the initial time and for the initial state. It uses finite-order approximations of the partial derivatives of the cost function and, successive higher-order differentiations of the HJB equation. The proposed method converts the HJB partial differential equation into a set of ordinary differential equations via the method of lines. Natural byproducts of the proposed method are the sensitivities of the cost function, which can be used to obtain approximations to the optimal controls at the initial time, in the event of initial state perturbations. Two numerical examples are considered to demonstrate the applications of this methodology. Results are compared to the respective open-loop solutions to determine the accuracy of the approximations.

AAS 09 – 407

On the Curse of Dimensionality in Fokker-Planck Equation

Mrinal Kumar, Suman Chakravorty and John Junkins, Texas A&M University

The curse of dimensionality associated with numerical solution of Fokker-Planck equation (FPE) is addressed in this paper. Two versions of the meshless, node-based partition of unity finite element method (PUFEM), namely, standard-PUFEM and particle-PUFEM are discussed. Both methods formulate the problem as weak form equations of FPE using local shape functions over a meshless cover of the solution domain. The variational (i.e. weak form) integrals are evaluated using quasi Monte-Carlo methods to handle the curse of dimensionality in numerical integration. The particle-PUFEM approach is presented as a generalization of standard-PUFEM and shown to provide flexibility in domain construction in high dimensional spaces and better handle the curse than the standard approach. In the current paper, it is used to solve FPE numerically for systems having up to five dimensional state-space on a small computing workstation, a result hence-far absent from numerical FPE literature. Coupled with local enrichment of the approximation space, it is shown that the particle-PUFEM approach can be used to immensely curb the curse of dimensionality in numerical solution of FPE, thus opening avenues for use of FPE in nonlinear filtering problems with long propagation times between measurements for space applications.

AAS 09 – 408

Trajectory Reconstruction of the ST-9 Sounding Rocket Experiment Using IMU and Landmark Data

R. S. Park, S. Bhaskaran, J. J. Bordi, Y. Cheng, A. J. Johnson, G. L. Kruizinga, M. E. Lisano, W. M. Owen, A. A. Wolf, Jet Propulsion Laboratory

This paper presents trajectory reconstruction of the ST-9 sounding rocket experiment using the onboard IMU data and descent imagery. The raw IMU accelerometer measurements are first converted into inertial acceleration and then used in trajectory integration. The descent images are pre-processed using a map-matching algorithm and unique landmarks for each image are created. Using the converted IMU data and descent images, the result from dead-reckoning and the kinematic-fix approaches are first compared with the GPS measurements. Then, both the IMU data and landmarks are processed together using a batch least-squares filter and the position, velocity, stochastic acceleration, and camera orientation of each image are estimated. The reconstructed trajectory is compared with the GPS data and the corresponding formal uncertainties are presented. The result shows that IMU data and descent images processed with a batch filter algorithm provide the trajectory accuracy required for pin-point landing.

AAS 09 – 425

Approximate Minimum-time Control Versus the PEG Control for Lunar Ascent

David G. Hull, University of Texas at Austin

The minimum-time control for constant-thrust lunar ascent is simplified by assuming that the thrust inclination is small. Because the downrange cannot be prescribed, the resulting control obeys a linear tangent law. The approximate minimum-time control can be determined completely analytically, that is, no iterations are required to obtain the control. Powered Explicit Guidance (PEG) is reviewed, and it is shown that the downrange cannot be prescribed. However, the control is made to satisfy a bilinear tangent law, so that the PEG control is not the minimum-time (minimum-fuel) control. Also, it is not completely analytical since an iteration is needed to calculate the final time. However, both controls used in a sample and hold guidance scheme perform equally well.

SESSION 16: CONJUNCTION ASSESSMENT II
Chair: Robert Hall, AGI

AAS 09 – 409

Discriminating Threatening Conjunctions with Data Fusion Principles

David Finkleman, Salvatore Alfano, and Timothy Carrico, Analytical Graphics, Inc.

Once a conjunction rises to immediate high probability, we determine how many other conjunctions the most significant collision partner might be exposed to within the assessment period. We then compound the probabilities of all of these estimated events in chronological order. The important measure is how likely the most valuable asset is to collide with anything during the assessment period, not just how likely the single highest probability is. In several cases, it is an order of magnitude more likely that the satellite will hit something than it is that it will experience the specific, high probability conjunction. We demonstrate the approach with recent conjunction events. We show that a mitigation maneuver developed against a specific high probability conjunction can make matters worse cumulatively during the interval after the maneuver is performed. There could be more possible conjunctions, and the probability of initially less probable conjunctions may increase.

AAS 09 – 410

Paper Withdrawn

AAS 09 – 411

Hazard Evaluation of the Space Debris in the Geostationary Orbit

Jorge Martins do Nascimento, Instituto Nacional de Pesquisas Espaciais, Brazil

The goal of this paper is to discuss the Hazard Evaluation or the Space Debris in the Geostationary Orbit, the adoption of mitigation measures for using the GEO orbit and to raise the possibility of adopting a concept of "state of the art" in regard to the remains of the third stages of rocket and engines used in the heydays of transfer orbits as well as the disposal of communication satellites at the end of its useful life.

AAS 09 – 412

Examination of Nonlinearity Based on the Second Order Expansion of the Orbit State Transition

Sergei Tanygin, Analytical Graphics, Inc.

The nonlinearity of dynamical systems is examined based on the second order expansion of their state transition. The analytical transitive Hessians are derived for Keplerian orbits using universal variable formulation. The second order bias and nonlinearity measures are derived based on the Hessians. Their possible applications for batch and sequential orbit determination as well as for improved long-term uncertainty propagation during conjunction analysis are discussed. The analytical results are validated numerically using several types of orbits.

AAS 09 – 413

Re-Examining Probability Dilution

Joseph H. Frisbee, Jr., United Space Alliance, LLC

In the last several years the concept of "Probability Dilution" or "Dilution of Probability" has been presented in the literature on satellite and orbital debris collision risk analysis. "Probability Dilution" proposes a quality criterion for accepting or rejecting a probability of collision risk estimate on the basis of where the probability estimate occurs with respect to the estimated maximum probability during the close approach event. In this paper evidence will be offered for why this criterion has no supportable basis. The evidence presented will consist of logical arguments supported by numerical examples and figures.

AAS 09 – 414

Analytic Launch Collision Avoidance Methodology

Felix R. Hoots, The Aerospace Corporation

The Aerospace Corporation (Aerospace) currently provides operational analysis to determine launch window times with minimal collision risk to on-orbit satellites. The current process is numerically intensive and may exceed computational capacity or timeline constraints as the satellite catalog and launch frequency grows. We have developed more sophisticated and efficient analytical processing algorithms to be able to meet planning and operational timelines for launch collision avoidance for our customers. The new analytical method provides excellent agreement with the current numerical method with a computer runtime reduction by a factor of 100 or more.

AAS 09 – 415

Anti-Satellite Engagement Vulnerability

Salvatore Alfano, Center for Space Standards and Innovation

This work uses simple orbital dynamics to initially assess the vulnerability of a satellite to a missile. This vulnerability can be represented as an engagement volume for a specific missile relative to its launch platform. Alternately, the vulnerability can be represented as a geographical footprint relative to satellite position that encompasses all possible launcher locations for a specific missile. An interceptor missile's final two-body orbital energy is determined from its burnout altitude and velocity. Assuming a ballistic trajectory from launch, the burnout energy is used to find the interceptor's initial velocity for a given launcher's altitude. Three engagement solutions are then found that account for spherical earth rotation. One solution finds the maximum missile range for an ascent-only trajectory while another solution accommodates a descending trajectory. In addition, the ascent engagement for the descending trajectory is used to depict a rapid engagement scenario. These preliminary solutions are formulated to address ground-, sea-, or air-launched missiles. The approach presented is not limited to satellites and is equally valid for determining vulnerability to mortars, artillery, SCUDs, Surface-to-Air missiles, etc.

AAS 09 – 416

Space Situation Monitoring Laboratory: An Integrated Web-Based Environment for Space Environment Information and Analysis

Justin F. McNeill, Jr., John M. Coggi, William H. Ailor, Thaddeus O. Cooper, Raymond L. Swartz, Jr. and Russell P. Patera, The Aerospace Corporation

Awareness of the near Earth space environment, including knowledge of space weather, pending close approaches, radio frequency interference, and other events that could affect the normal operations of a space vehicle, is becoming more important as dependence on space systems increases. The Space Situation Monitoring Laboratory (SSML) is a prototype, web-based system designed to detect, display, monitor, and archive anomalous events and provide automated notifications to researchers and engineers. The system employs new algorithms and tools for the monitoring, analysis, and study of the space environment. SSML includes information on satellite ephemerides, predicted satellite closest approaches, space weather, and satellite orbital changes that are indicative of maneuvers, collisions, explosions, or even atmospheric effects. The system uses displays and visualizations with Web Services infrastructure to present information in an intuitive fashion that can lead to a broader understanding of the current satellite environment.

SESSION 17: SATELLITE CONSTELLATIONS/TETHERED SATELLITES
Chair: Dr. Daniele Mortari, Texas A&M University

AAS 09 – 417

A Preliminary Study of the Dynamics and Control of the CubeSail Spacecraft

Andrew Pukniel, Victoria Coverstone, John Warner and Rodney Burton, University of Illinois at Urbana-Champaign

The proposed study addresses two issues related to slow emergence of solar sailing as a viable space propulsion method. The low technology readiness level and complications related to stowage, deployment, and support of the sail structure are both addressed by combining the CU Aerospace and University of Illinois-developed UltraSail and Cubesat expertise to design a small-scale solar sail deployment and propulsion experiment in low Earth orbit. The study analyzes multiple aspects of the problem from initial sizing and packaging of the solar sail film into two Cubesat-class spacecraft, through on-orbit deployment dynamics, attitude control of large and flexible space structure, and predictions of performance and orbital maneuvering capability.

AAS 09 – 418

Cost Effectiveness of On-Orbit Servicing

Tiffany Rexius, Jackson & Tull

This study was performed to model on-orbit servicing (OOS) of a pre-existing Low Earth Orbit and geostationary constellation. A conceptual model of each spacecraft was developed to determine mass and power allocation required based on the mission of the spacecraft. An OOS mass was added to the spacecraft which represented the mass of the components necessary to allow the spacecraft to be docked with. The servicing missions modeled were refueling, replacement of parts, and relocation. The driving factor of cost was sensitivity to OOS mass. For most constellations, OOS was not cost effective unless the OOS mass was very low.

AAS 09 – 419

Long-Term Stability of Flower Constellations under Planetary Oblateness

Troy A. Henderson and Martín Avendaño, Texas A&M University

A study of planetary oblateness (specifically J_2)on the stability of Flower Constellations is presented. The result is an investigation of station keeping requirements as well as a newly developed theory of Flower Constellation design taking into account the major oblateness perturbation.

AAS 09 – 421

New Color Visualization for Satellite Constellation Coverage

Paul J. Cefola, Consultant in Aerospace Systems; John E. Draim, Consultant

This paper introduces a new color visualization of the coverage characteristics of a multiple satellite constellation. Each of the generated plots gives color-coded coverage information vs. user earth-fixed latitude and longitude.

AAS 09 – 422

The Determination of Time-Variable Gravity from a Constellation of Non-Dedicated Satellites

Brian C. Gunter, Pavel Ditmar and João Encarnação, Delft University of Technology

This study will assess the feasibility of using a constellation of non-dedicated satellites to determine the Earth's time-variable gravity field. Precise orbit data from the FORMOSAT-3/COSMIC satellite constellation will be processed and the results will be compared to theoretical predications. Provided accurate knowledge the satellite orbits through GPS positioning only, the constellation should be able to provide information about the large scale (> 1000 km), high frequency (< 1 month) variations in the gravity field. The concept would also provide current and future dedicated gravity field missions with valuable information at the low degrees, thereby improving the overall recovery of the full spectrum of time-variable gravity. This is valuable not only for Earth observation, but for topics in mission design and orbit determination.

AAS 09 – 423

Numerical Computation of Optimal Electrodynamic Orbit Transfers

Paul Williams, Delft University of Technology

Electrodynamic tether systems have the potential for allowing orbital maneuvers to be undertaken with little or no propellant. However, when operated in this mode, the current must be modulated on a fast timescale compared to the variation in the average orbital elements. This paper introduces a new numerical technique for calculating optimal trajectories for general dynamical systems where the dynamics evolve on multiple timescales. The method combines quadrature and pseudospectral methods using the Chebyshev-Gauss-Lobatto points, which are shown to be ideal for handling timescale separation. The resulting nonlinear programming problem generates a significantly reduced problem size compared with solving the full-scale problem. Numerical results for a problem with an analytic solution show that the method achieves high accuracy. Results generated for hanging and spinning electrodynamic tethers demonstrate that spinning electrodynamic tethers can be more efficient for orbital maneuvering.

SESSION 18: TRAJECTORY OPTIMIZATION III
Chair: Dr. David Spencer, Penn State University

AAS 09 – 424

An Assessment of Multiple Satellite-Aided Capture at Jupiter

Alfred E. Lynam, Kevin W. Kloster and James M. Longuski, Purdue University

Satellite-aided capture is a mission design concept used to reduce the delta-v required to capture into a planetary orbit. The technique employs close flybys of a massive moon to reduce the energy of the planet-centered orbit. A sequence of close flybys of two or more of the Galilean moons of Jupiter may decrease the delta-v cost of Jupiter orbit insertion. A Ganymede-Io sequence saves 207 m/s of delta-v over a single Io flyby. These novel sequences have potential to benefit both NASA‘s Jupiter Europa orbiter mission and ESA‘s Jupiter Ganymede orbiter mission.

AAS 09 – 426

An Optimal Initial Guess Generator for Entry Interface Targeters

Juan S. Senent, Odyssey Space Research

If a pure numerical iterative approach is used, targeting entry interface (EI) conditions for nominal and abort return trajectories or for correction maneuvers can be computationally expensive. This paper describes an algorithm to obtain an optimal impulsive maneuver that generates a trajectory satisfying a set of EI targets: inequality constraints on longitude, latitude and azimuth and a fixed flight-path angle. Most of the calculations require no iterations, making it suitable for real-time applications or large trade studies. This algorithm has been used to generate initial guesses for abort trajectories during Earth-Moon transfers.

AAS 09 – 427

Constrained Optimal Orbit Design for Earth Observation Satellites Based on User Requirements

Sharon D. Vtipil and Brett Newman, Old Dominion University

The purpose of this paper is to demonstrate user requirements for a satellite observation mission can be used to determine a constrained optimal orbit based on observation site requirements, observation condition restraints, and sensor characteristics. The design process is outlined starting with mapping the user requirements into constraints. The cost function and optimization process are then discussed. Global and regional case studies are presented to show the effectiveness of the design process.

AAS 09 – 428

Broad Search and Optimization of Solar Electric Propulsion Trajectories to Uranus and Neptune

Damon Landau, Try Lam and Nathan Strange, Jet Propulsion Laboratory

A procedure to produce a large variety of trajectories to Uranus and Neptune is presented. A small set of exceptional trajectories emerges from this broad search and expands the range of missions available to these planets. Payload mass increases dramatically when a Jupiter flyby is available, and the choice of gravity-assist sequence has a greater effect on performance than the choice of propulsion system. The combination of solar electric propulsion and gravity assists enable missions with larger payloads than with chemical propulsion over a broad range of flight times and power levels. Results are provided for both aerocapture and chemical orbit insertion.

AAS 09 – 429

Autonomous Multi-Rover Trajectory Planning Using Optimal Control Techniques

Michael A. Hurni, Pooya Sekhavat and I. Michael Ross, Naval Postgraduate School

Future manned and robotic space missions call for autonomous coordination and control of planetary rovers. This paper presents the implementation of a pseudospectral (PS) optimal control-based algorithm for autonomous trajectory planning and control of several unmanned ground vehicles (UGV) with real-time information updates. The mission of the UGVs is to traverse from their initial start points and reach their targets in minimum time, with maximum robustness, while avoiding obstacles (static and dynamic) and each other. Control solutions are repeatedly recomputed and updated throughout the vehicles' missions. Simulation results illustrate the performance of the planner in various multi-vehicle scenarios.

AAS 09 – 431

Design of Guidance Laws for Lunar Pinpoint Soft Landing

Jian Guo, Technical University of Delft; Congying Han, University of Surrey

Future lunar missions ask for the capability to perform precise Guidance, Navigation and Control (GNC) to the selected landing sites on the lunar surface. This paper studies the guidance issues for the lunar pinpoint soft landing problem. The primary contribution of this paper is the design of descent guidance law based on the Pontryagin maximum principle. The simulation shows that the proposed polynomial guidance law can achieve precise pinpoint landing. However it is sensitive to the selection of several parameters. Suggestions on lunar pinpoint soft landing strategies are also given according to the simulation results.

SESSION 19: PLANETARY, ASTEROID AND DEEP SPACE MISSIONS II
Chair: Yanping Guo, APL

AAS 09 – 432

Mission Design of Guided Aero-Gravity Assist Trajectories at Titan

Jordi Casoliva and Daniel T. Lyons, Jet Propulsion Laboratory

Interplanetary waveriders use atmospheric lift to increase the effectiveness of gravity assist maneuvers by increasing the bending angle at the expense of departure speed relative to the moon or planet used for the gravity assist. Our recently developed guidance algorithm for Aero-Gravity Assist (AGA) targets an outgoing V-infinity vector at the end of the atmospheric flythrough and has been applied to flybys at Titan. Detailed simulations of the AGA atmospheric flyby segments for two different reference missions will be used to evaluate the possible difficulties associated with achieving and controlling such trajectories. Selected Titan aero-gravity assisted mission options include directly transferring from the hyperbolic Saturn arrival trajectory to other moons, including resonant orbits that return to Titan. The high departure speeds require very accurate targeting of both the departure speed and direction to minimize cleanup propellant requirements. Preliminary results show that Titan aero-gravity assists create a wide range of mission options in the Saturnian system.

AAS 09 – 433

Spacecraft Trajectory Design for Tours of Multiple Small Bodies

Brent William Barbee, George W. Davis and Sun-Hur Diaz,
Emergent Space Technologies, Inc.

Spacecraft science missions to small bodies (asteroids and comets) have historically visited only one or several small bodies per mission. Our research goal is to create a trajectory design algorithm that generates trajectory sets allowing a spacecraft to visit a significant number of asteroids during a single mission. There are several hundred thousand known asteroids, and this huge search space makes identifying optimal or feasible asteroid itineraries an NP-complete combinatorial minimization problem. An algorithm has been developed to traverse the search space and generate solutions, enabling trajectory design for multiple small body tours using available spacecraft propulsion technology.

AAS 09 – 434

Repeated Shadow Track Orbits

Ahmed Gad and Ossama Abdelkhalik, Michigan Technological University

This paper introduces a new set of orbits, the “Repeat Shadow Track Orbits.” In these orbits, the shadow of a spacecraft on the Earth visits the same locations periodically every desired number of days. The J_2 perturbation is utilized to synchronize the spacecraft shadow motion with both the Earth rotational motion and the Earth-Sun vector rotation. Motivation for the design of new shadow track orbits comes from the need to save energy. The general mathematical model to design a Repeated Shadow Track Orbit (RSTO) is presented within this paper. RSTOs’ conditions are formulated and numerically solved. Results show the feasibility of RSTOs. An optimization process is developed to maximize the shadow duration over a given site. A Genetic Algorithm (GA) technique is utilized for optimization.

AAS 09 – 435

Leveraging Flybys of Low Mass Moons to Enable an Enceladus Orbiter

Nathan J. Strange, Jet Propulsion Laboratory; Stefano Campagnola, University of Southern California; and Ryan P. Russell, Georgia Institute of Technology

As a result of discoveries made by the Cassini spacecraft, Saturn’s moon Enceladus has emerged as a high science-value target for a future orbiter mission. However, past studies of an Enceladus orbiter mission found that entering Enceladus orbit either requires a prohibitively large orbit insertion delta V (> 3.5 km/s) or a prohibitively long flight time. In order to reach Enceladus with a reasonable flight time and delta V budget, a new tour design method is presented that uses gravity-assists of low-mass moons combined with v-infinity leveraging maneuvers. This new method can achieve Enceladus orbit with a combined leveraging and insertion delta V of ~1 km/s and a 2.5 year Saturn tour.

AAS 09 – 436

On the Orbit Selection of the Space Solar Telescope ADAHELI

Fabio Curti and Giuseppe Russo, University of Rome "Sapienza"; Francesco Longo, Italian Space Agency

ADAHELI (ADvanced Astronomy for HELIophysics) is a project of the Italian Space Agency to carry out a small mission on the investigation of solar photospheric and chromospheric dynamics, via high-resolution spectro-polarimetric observations in the near-infrared spectral range. In the frame of the ADAHELI project, the present study deals with the orbit selection in order to satisfy the mission requirements. The main driver, in searching the suitable orbit, is the doppler shift that affects the orbiting telescope and which has to be kept within required bounds. Three groups of orbits are analyzed: Sun-Synchronous Circular Orbits, Sun-Synchronous Frozen Elliptical Orbits and Frozen Elliptical Orbits. To compare these orbits, two parameters must be considered based on the mission requirements of the time percentage of continuous observations in the admissible doppler shift ranges.

AAS 09 – 437

Paper Withdrawn

SESSION 20: ORBITAL DYNAMICS II

Chair: Dr. Felix Hoots, The Aerospace Corporation

AAS 09 – 438

Optimal Low-Energy Transfers in the Concentric Circular Restricted Four-Body Problem

Fady M. Morcos and Cesar A. Ocampo, The University of Texas at Austin

The problem of transfer in the Concentric Circular Restricted Four-Body Problem, CR4BP is considered in this paper. The paper deals with the transfer of a spacecraft between two coplanar circular orbits about two natural satellites, M_2 and M_3, of a central body, M_1. The mission is broken down into segments in two separate three-body systems, which are later patched together to complete the transfer; similar to the patched conics technique utilized in the relative two-body problem. The invariant stable and unstable manifold structures of the collinear equilibrium points, L_1 and L_2, of both systems, form networks of trajectories, serving as low energy passageways. Intersections between those tubes provide the framework for designing the transfer. The patched solution is used as an initial guess, and later integrated in the CR4BP gravitational model, including direct and indirect perturbations. A gradient-based targeting algorithm is used to achieve the end point boundary conditions. Due to the sensitivity of low energy transfers, analytical derivatives are used to aid the convergence process. The necessary conditions for local optimality of the transfer are verified with Primer Vector Theory.

AAS 09 – 439

Ballistic Coefficient and Density Estimation

Craig A. McLaughlin, Andrew Hiatt, Eric Fattig and Travis Lechtenberg,
University of Kansas

Atmospheric density modeling is the greatest uncertainty in the dynamics of low Earth satellite orbits. This paper examines the effects of ballistic coefficient errors in using precision orbits to estimate total density along the satellite orbit. The density is estimated using Challenging Minisatellite Payload (CHAMP) precision orbit data. The accuracy of the precision orbit derived density is compared to CHAMP accelerometer derived density with various values of initial ballistic coefficient. The paper examines the ability of the estimation process to estimate ballistic coefficient in the presence of errors in the initial guess for ballistic coefficient.

AAS 09 – 440

Mean Element Propagations Using Numerical Averaging

Todd A. Ely, Jet Propulsion Laboratory

The long-term evolution characteristics (and stability) of an orbit are best characterized using a mean element propagation of the perturbed two body variational equations of motion. The averaging process eliminates short period terms leaving only secular and long period effects. In this study, a non-traditional approach is taken that averages the variational equations using adaptive numerical techniques and then numerically integrating the resulting EOMs. Doing this avoids the Fourier series expansions and truncations required by the traditional analytic methods. The resultant numerical techniques can be easily adapted to propagations at most solar system bodies.

AAS 09 – 441

Arbitrary Order Vector Reversion of Series and Implicit Function Theorem

James D. Turner, Manoranjan Majji and John L. Junkins, Texas A&M University,

High-order modeling and optimization methods are required for handling challenging applications where nonlinear behaviors are important. Vector-valued Taylor series math models provide the core analysis tools for analyzing and optimizing the performance of complex mechanical systems. Two specialized mathematical operations frequently appear, including: (1) successive approximation techniques, and (2) implicit function theorem calculations. Both of these analysis techniques require calculations for vector-valued composite function calculations, where implicit rate calculations represent a specialized composite function calculation. For the special case of scalar function calculations, since 1857, composite function calculations have been handled by invoking the combinatorically motivated mathematical identity of Faá di Bruno. Vector-valued generalizations of di Bruno's formula have been proposed, but the resulting algorithms are very difficult to apply in real-world applications. This paper presents reformulation of the vector-valued di Bruno formula that allows arbitrary order calculations to be recursively generated. Three steps are required for developing algorithms for handling arbitrary order vector generalizations for composite and implicit function calculations. First, Faá di Bruno's identity is replaced with an algorithmically simpler series solution discovered by George Scott in 1861. Second, abstract compound data structures are introduced for managing calculations, which leads to a generalized matrix operator where the indexed object components represent tensors of various orders. Third, generalized product operators are introduced for recursively generating the tensor math models required by Scott's formula. Recursive algorithms are comprehensively addressed for both composite function and implicit rate calculations. Several numerical examples are presented implicit rate calculations, as well as closed-form solutions for Lagrange's implicit function series expansions. The resulting algorithms are recursive, exact, very fact, and scale to arbitrary order.

AAS 09 – 442

Earth-Moon Trajectory Design Using Lagrange Implicit Function Theorem

Manoranjan Majji, James D. Turner and John L. Junkins,
Texas A&M University, College Station, Texas

Trajectory design for the Earth-Moon flight of a spacecraft is considered in the present paper. The optimal control problem associated with the transfer trajectory is presented, detailing the resulting two point boundary value problem. Application of Lagrange implicit function theorem to nominal solutions obtained is subsequently detailed. The practical problem of uncertainty associated with impulse application is considered and the sensitivities of the optimal program are utilized to estimate the evolution of the associated impulsive uncertainty. The results obtained conclusively demonstrate the nonlinearity of the problem, in addition to providing a holistic design tool for generation of neighboring optimal solutions and performing parametric studies.

AAS 09 – 443

Low-Energy Ballistic Transfers to Lunar Halo Orbits

Jeffrey S. Parker, Jet Propulsion Laboratory

Recent lunar missions have begun to take advantage of the benefits of low-energy ballistic transfers between the Earth and the Moon rather than implementing conventional Hohmann-like transfers. Both Artemis and GRAIL plan to implement low-energy lunar transfers in the next few years. This paper explores the characteristics and potential applications of many different families of low-energy ballistic lunar transfers. The transfers presented here begin from a wide variety of different orbits at the Earth and follow several different distinct pathways to the Moon. This paper characterizes these pathways to identify desirable low-energy transfers for future lunar missions.

AAS 09 – 444

State Transition Matrix Approximation Using a Generalized Averaging Method

Yuichi Tsuda, Institute of Space and Astronautical Science/Japan Aerospace Exploration Agency; Daniel J. Scheeres, University of Colorado at Boulder

This paper presents a method for approximating the state transition matrix for orbits around a primary body and subject to arbitrary perturbations. A generalized averaging method is employed to isolate the high and low frequency regions of the perturbation terms, and construct a functional form of the approximate state transition matrix composed only of elementary analytic functions. The resulting state transition matrix is expressed with a small number of constant parameter matrices and osculating orbit parameters at an initial epoch, and is valid for tens of orbital revolutions without having to update the parameters. Numerical simulations show that this method is valid for arbitrary eccentricity orbits with semimajor axis ranging from LEO up to around 10 Earth radii when applied to Earth orbits. This method has been developed for implementation onboard spacecraft for high accuracy formation flying missions. Furthermore, it is shown that the symplectic property, which is a fundamental mathematical structure of Hamiltonian systems, can be incorporated into the method. This not only reduces the number of parameters required for approximations, but also preserves the physically true structure of the state transition matrix and provides some important properties that are practical and useful for onboard computation.

AWARDS BANQUET PRESENTATION

Featured Speaker

William “Red” L. Whittaker, Carnegie Mellon University’s Robotics Institute

Red Whittaker is now competing for the $2 million Google Lunar X PRIZE for privately landing a robot on the moon, which is the topic of his presentation. Only a brief abstract and biography for this presentation was available for publication.

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