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Middle: The March 7th 1970 total solar eclipse. Credit: NSO/AURA/NSF.
Right-top: Jupiter's great red spot, captured by the Juno spacecraft.
Credit: NASA/JPL-Caltech/SwRI/MSSS/Jason Major.
Right-middle: Parker Solar Probe, illustrated with heat shield on Sunward side. Credit: JHU/APL.
Right-bottom: ULA's CubeSat Launch Program.
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ASTRODYNAMICS 2017

Volume 162

ADVANCES IN THE ASTRONAUTICAL SCIENCES

Edited by
Jeffrey S. Parker
John H. Seago
Nathan J. Strange
Daniel J. Scheeres

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FOREWORD

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

Astrodynamics 2017, Volume 162, Advances in the Astronautical Sciences, consists of four parts totaling about 4,064 pages, plus a CD ROM/digital format version which also contains all the available papers. Papers which were not available for publication are listed on the divider pages of each section. A chronological index and an author index appear at the end of the main linking file, and are appended to the fourth part of the volume.

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

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

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

AAS/AIAA ASTRODYNAMICS VOLUMES

Astrodynamics 2017 appears as Volume 162, *Advances in the Astronautical Sciences*. This publication presents the complete proceedings of the AAS/AIAA Astrodynamics Specialist Conference 2017.

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

AAS/AIAA SPACEFLIGHT MECHANICS VOLUMES

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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Robert H. Jacobs, Series Editor

PREFACE

The 2017 Astrodynamics Specialist Conference was held at the Skamania Lodge in Stevenson, Washington, in the heart of the Columbia Gorge, from August 20–24, 2017. The meeting was sponsored by the American Astronautical Society (AAS) Space Flight Mechanics Committee and co-sponsored by the American Institute of Aeronautics and Astronautics (AIAA) Astrodynamics Technical Committee. Approximately 261 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. 95 students registered, 4 retirees, and 162 professionals.

There were 240 technical papers, including 22 technical posters, presented in 26 sessions on topics related to space-flight mechanics and astrodynamics. There were three special sessions with focuses on Outer Planets Exploration, Constrained Global Trajectory Optimization, and Humans Beyond Earth Orbit.

The meeting included the first Student Competition; 7 student teams competed to design a mission to the asteroid (469219) 2016 HO3: an asteroid that is co-orbiting the Sun with Earth in a three-body orbit. Special recognition goes out to the University of Colorado's team, who placed first in the competition; 2nd place went to Purdue University; 3rd place went to the University of Arizona. Congratulations to all teams.

The meeting attendees had a special opportunity to attend the 2017 total solar eclipse; a special viewing was organized in Madras, Oregon, including special tours of the Erickson Collection Museum in Madras. Monday's activities also included the student competition presentations, the dedicated poster presentations, and the keynote speaker Dr. Louis Freidman, speaking on "Political Advocacy for the Planets."

The meeting included social networking events each evening, in the open air with views of the Columbia Gorge.

The editors extend their gratitude to the Session Chairs who made this meeting successful: Manoranjan Majji, Juan Arrieta, Jon Sims, Rodney Anderson, Roby Wilson, Brian Gunter, Kyle DeMars, Carolin Frueh, Nitin Arora, Ryan Russell, Angela Bowes, Jay McMahon, Paul Thompson, Christopher Roscoe, Stefano Casotto, Roberto Furfaro, Jacob Englander, Jonathan Aziz, Matthew Wilkins, Diane Davis, Renato Zanetti, Sean Wagner, Jacob Darling, Christopher D'Souza, Andrew Sinclair, and Raymond Merrill.

Our gratitude also goes to Renato Zanetti, Sean Wagner, Roberto Furfaro, Chris Roscoe, Robert Jacobs, Kathy Howell, Roby Wilson, David Spencer, James Kirkpatrick, and Jim Way for the support and assistance. We thank Michelle Forster, who hosted our conference attendees at the eclipse viewing in Madras at the Erickson Collection Museum; we thank the museum for the tours and hospitality.

Dr. Jeffrey S. Parker
Advanced Space
AAS Technical Chair

Dr. Nathan J. Strange
NASA Jet Propulsion Laboratory
AAS General Chair

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Analytical Graphics, Inc. (AGI)
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University of Colorado
AIAA General Chair

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Session 8: Kyle DeMars

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POINTING JITTER CHARACTERIZATION FOR VARIOUS SSL 1300 SPACECRAFT WITH SIMULATIONS AND ON-ORBIT MEASUREMENTS

Byoungsam (Andy) Woo[*] and Erik A. Hogan[†]

Jitter - line of sight instability or high frequency platform oscillation - is one of the critical performance measures in various pointing sensitive missions, especially high resolution imaging or optical communication missions.1,2 If the jitter characteristics of the platform, Earth orbiting satellites in this research, is available at an early phase of development, the imaging or optical communication payload design can be largely optimized and simplified. This paper describes jitter characterization for SSL 1300 series satellites by modeling/simulations and on-orbit measurements in various operational modes. The measured jitter of various SSL 1300 satellites meets or exceeds various jitter requirements for high resolution imaging and optical communications missions.

[View Full Paper]

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MODEL PREDICTIVE CONTROL AND MODEL PREDICTIVE Q-LEARNING FOR STRUCTURAL VIBRATION CONTROL

Minh Q. Phan* and Seyed Mahdi B. Azad*

This paper describes the relationship between Model Predictive Control (MPC) and Q-Learning, and formulates an algorithm called Model Predictive Q-Learning that integrates the two concepts. As a unifying theme, the paper explains how the Linear Quadratic Regulator (LQR), MPC, Q-Learning, and Model Predictive Q-Learning solve the same structural vibration control problem, and how the Q-Learning approach naturally handles both continuous and discrete-action inputs. The relationship between Model Predictive Q-Learning and standard Q-Learning is analogous to the relationship between MPC and LQR. [View Full Paper]

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AAS 17-622

DECENTRALIZED FINITE-TIME ATTITUDE CONTROL FOR MULTI-BODY SYSTEM WITH TERMINAL SLIDING MODE

Jinyue Li[*] and Jingrui Zhang[*]

Terminal sliding mode (TSM) is a finite-time control related design method. TSM controller ensure the system`s trajectories converge to equilibrium in finite time. It also offers higher-accuracy and better anti-disturbance properties. Decentralized control theory is originated from large-scale system`s control problem. By separating one system into several subsystems, and control the subsystems with several independent controllers, a decentralized control is presented. Decentralized control gives system greater efficiency and higher robustness. By combing the concept of decentralized control and TSM control. A Decentralized TSM controller is proposed. The designed control law is applied to a multibody system. Numerical simulation is presented to show the effectiveness of the newly designed controller. [View Full Paper]

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AAS 17-646

ITERTIVE LEARNING CONTROL DESIGN WITH LOCAL LEARNING

Jianzhong Zhu[*] and Richard W. Longman[†]

Many real world situations have a linear system with input through a zero order hold and sampled output. Often one knows the desired output and would like to solve the inverse problem of finding that input that produces this output. For the majority of physical systems this results in an unusable input that grows exponentially with time and alternates sign each time step. Recent results demonstrated a new stable inverse method produced by allowing two or more zero order holds between each time step for which one that asks for zero error. This addresses a basic problem and has the potential to address difficulties in many control approaches. In particular, this paper treats problems such as a factory robot repeatedly starts from a home position, going to a newly arrived object where it performs a high precision task, and then returns to home. High accuracy tracking is only needed for the task part of the trajectory, during which we make use of the stable inverse result. Other parts of the trajectory use a typical quadratic cost control that compromises tracking accuracy for reduced control effort. The purpose of this paper is to develop a method to create such desired trajectories with a zero-error tracking interval without involving an unstable inverse. Then an easily implementable feedback version is created optimizing the same cost every time step from the current measured position. The above methods are only as good as the model used, so an Iterative Learning Control (ILC) algorithm is created to iteratively learn to give local zero error in the real world while using an imperfect model. The approach also gives a method to apply ILC to endpoint problems without specifying an arbitrary trajectory to follow to reach the endpoint. This creates a method for ILC to apply to such problems without asking for accurate tracking of a somewhat arbitrary trajectory to accomplish learning to reach the desired endpoint.

[View Full Paper]

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AAS 17-656

REPETITIVE CONTROL DESIGN FOR THE POSSIBLE DIGITAL FEEDBACK CONTROL CONFIGURATIONS

Tianyi Zhang* and Richard W. Longman†

Digital repetitive control (RC) seeks to make a feedback control system converge to zero tracking error at each sample time following a periodic command. Many spacecraft sensors perform repeated periodic scanning maneuvers. Zero tracking error might best be accomplished by observing previous period error and computing the needed correction from the system inverse. Unfortunately, discrete time equivalents of continuous time models usually have zeros introduced outside the unit circle, making the inverse model unstable. The asymptotic pattern of zero locations is known in general for each pole excess. One can cancel all dynamics inside the unit circle, but one cannot cancel the zeros outside. The authors and co-workers have developed several RC methods to design FIR filters that compensate these zeros, each making its own pattern of additional zeros outside. Previous literature considers many pole excesses, but normally only considers a continuous time feedback system converted to discrete time. More general applications need to handle general digital feedback control systems, with digital controller, but continuous time plant, possible anti-aliasing filter, possible sensor noise filter, etc. It is the purpose of this paper to examine what the possible patterns of zero locations can be for these different situations. New situations occur with repeated original zero pattern outside the unit circle, or neighboring zeros outside, or the union of zero patters for two different pole excesses. Each RC approach addresses these situations differently. Generally, the RC based on inverse frequency response tends to produce the best result, but the other approaches develop understanding of the source of observed compensator zero patterns.

[View Full Paper]

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AAS 17-657

DYNAMIC ANALYSIS OF VIBRATION ISOLATION SYSTEM WITH MAGNETIC SUSPENSION ON SATELLITES

Yao Zhang,* Chao Sheng,† Quan Hu,‡ Mou Li,§ Zixi Guo and Rui Qi††**

Beijing Institute of Technology, Beijing, 100081, P.R. China

The vibration isolation platform is widely used to isolate the micro vibration that is harmful to the sensitive payloads on satellites. The traditional passive vibration isolation platform has difficulty in isolating vibration with low frequency and designing the stiffness and damping parameters. In this work, a new kind of vibration isolation platform whose actuators are based on the magnetic suspension techniques is presented. The first step studies the force between two coils with currents and gives a simplified model of the force. The model of a single strut of the vibration isolation platform is described and the control currents are designed. Then the dynamic model of the vibration isolation platform is built. Based on this dynamic model, the electromagnetic coupling among struts is discussed, the stability and the parameters sensitivity of the platform are analyzed. The accuracy and efficiency of this study are validated through numerical simulations of an attitude control loop using the vibration isolation platform.

Key words: magnetic suspension techniques; vibration isolation. [View Full Paper]

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AAS 17-670

ROOT LOCUS OF ZEROS OF DISCRETE TIME SYSTEMS AS A FUNCTION OF SAMPLE RATE

Wenxiang Zhou* and Richard W. Longman†

Root locus plots are one of the basic design tools in classical control. They help the designer tune control gains which appear linearly in the coefficients of the closed loop characteristic polynomial. And they give considerable intuition to the designer, based on the simple rules that root loci must follow. When designing a control system, one wants to know where the zeros are, but when designing a digital control system new issues appear. The original zero locations when mapped to discrete time are functions of the new parameter, the sample time T (as well as the pole locations). In addition, new zeros are usually introduced by the discretization process. The purpose of this paper is to give a general understanding of the nature of root loci of discrete time transfer function zeros as a function of this parameter T. We consider the complete range of values from T equal zero to infinity to understand the full plot. Reasonable sample rates will only use part of the plots. The characteristic polynomial coefficients are nonlinear functions of T so the usual root locus rules do not apply. One can be amazed at how the usual root locus rules are repeatedly violated, and what new kinds of unexpected behavior can be observed.

[View Full Paper]

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PROOF OF TWO NEW STABLE INVERSES OF DISCRETE TIME SYSTEMS

Xiaoqiang Ji,[*] Te Li[†] and Richard W. Longman[‡]

Digital control needs discrete time models, but conversion from continuous time, fed by a zero order hold, to discrete time introduces sampling zeros which are outside the unit circle in the majority of systems. Also, some systems are already non-minimum phase in continuous time. In both cases, the inverse problem to find the input necessary to produce a desired output, produces an unstable control action. This prevents many control approaches from making use of inverse models. This paper presents two new methods of producing stable inverses for such systems. Proofs are given for each. The approach develops a matrix factorization of the stably invertible part of the system and the remaining part. One stable inverse gives zero error at every sample time, except for one or more time steps at the beginning of the trajectory, the number equal to the number of non-minimum phase zeros. The second stable inverse asks to increase the sample rate by the number of non-minimum phase zeros, and ask for zero error at the original sample times. Control actions at the new time steps are determined by the minimum norm solution of chosen underdetermined equations. Having a stable inverse opens up opportunities for many control design approaches including Iterative Learning Control, Repetitive Control, Linear Model Predictive Control, and *p*-step ahead control that generalizes one step ahead control. [View Full Paper]

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AAS 17-686

IMPROVED DETUMBLING CONTROL FOR CUBESAT BY USING MEMS GYRO

Dong-Hyun Cho,[*] Dong-Hun Lee[†] and Hae-Dong Kim[‡]

In this paper, we suggest the improved detumbling control for cubesat by using MEMS gyro. In general, satellite have to perform the detumbling attitude maneuver after it separated from the launch vehicle because it has an initial separation angular velocity. For this control mode, satellite uses only a minimum number of sensors and actuators for reasons of power consumption and etc. In the past, satellite did not measure the own tumbling rate directly without gyro. Therefore, a B-dot controller using a magnetic field sensor and a magnetic torquers was widely used for this attitude maneuver. However, since the MEMS gyro is embedded in the on-board computer for cubesat, it is possible to measure the angular velocity for the detumbling controller. However, during the magnetic torquers are operating, it is difficult to measure the correct magnetic field for magnetic interference from magnetic torquers. For this reason, the performance of previous detumbling control is limited. Therefore, in this paper, we suggested a simple filter to estimate the magnetic field data during the magnetic torquers are operating and it can be possible to reduce the settling time for detumbling mode. And it is also possible to control the switching time between magnetic sensor and actuator by using covariance information from filter. [View Full Paper]

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AAS 17-691

TIME OPTIMAL CONTROL OF A DOUBLE INTEGRATOR PLANT WITH FEEDBACK DYNAMICS

C. S. Monk[*] and M. Karpenko[†]

Optimal control solutions are typically implemented in open-loop based on nominal system and environmental parameters. However, ignorance of the true values of system parameters can undermine the optimal control solution. While conventional feedback can compensate for significant levels of uncertainty, this comes at the expense of optimality. This paper examines minimum time rotational maneuvers for a double integrator plant, a canonical model for a variety of space systems, with a two degree-of-freedom control architecture consisting of a traditional proportional-derivative feedback loop combined with a feed-forward signal. A real-time optimal control approach is developed for computing the feed-forward signal using a combination of optimal control analysis and classical control analysis techniques. The performance of this strategy is evaluated.

[View Full Paper]

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AAS 17-730

FULLY-COUPLED DYNAMICAL JITTER MODELING OF VARIABLE-SPEED CONTROL MOMENT GYROSCOPES

John Alcorn,[*] Cody Allard[*] and Hanspeter Schaub[†]

Control moment gyroscopes (CMGs) and variable-speed control moment gyroscopes (VSCMGs) are a popular method for spacecraft attitude control and fine pointing. However, since these devices typically operate at high wheel speeds, mass imbalances within the wheels act as a primary source of angular jitter. Although these effects are often characterized through experimentation in order to validate pointing stability requirements, it is of interest to include jitter in a computer simulation of the spacecraft in the early stages of spacecraft development. An estimate of jitter amplitude may be found by modeling imbalance torques as external disturbance forces and torques on the spacecraft. In this case, mass imbalances are lumped into static and dynamic imbalance parameters, allowing jitter force and torque to be simply proportional to wheel speed squared. A physically realistic dynamic model may be obtained by defining mass imbalances in terms of a wheel center of mass location and inertia tensor. The fully-coupled dynamic model allows for momentum and energy validation of the system. This is often critical when modeling additional complex dynamical behavior such as flexible dynamics and fuel slosh. This paper presents a generalized approach to VSCMG imbalance modeling of a rigid spacecraft hub with *N* VSCMGs. Implementations of the fully-coupled VSCMG model derived within this paper are released open-source as part of the Basilisk astrodynamics software. [View Full Paper]

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AAS 17-774

ELECTRICAL-POWER CONSTRAINED ATTITUDE STEERING

Harleigh C. Marsh,[*] Mark Karpenko[†] and Qi Gong[‡]

This paper examines the effectiveness of reducing the energy consumption of a reaction-wheel array over the course of a slewing maneuver by steering the attitude of the spacecraft, in situations where it is not possible to command the reaction wheel torque directly. To explore this avenue, a set of constrained nonlinear non-smooth L1 optimal-control problems are formulated and solved. It is demonstrated that energy consumption, dissipative losses, and peak-power load, of the reaction-wheel array can each be reduced substantially, by controlling the input to the attitude control system through attitude steering, thereby avoiding software modifications to flight software. [View Full Paper]

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AAS 17-775

STOCHASTIC ATTITUDE CONTROL OF SPACECRAFT UNDER THRUST UNCERTAINTY

Alen E. Golpashin,[*] Hoong C. Yeong,[*] Koki Ho[†] and N. Sri Namachchivaya[‡]

This study aims to address the problem of attitude control of spacecraft in presence of thrust fluctuations, which lead to stochastic accelerations. Many satellites and spacecraft rely on electric propulsion and other low thrust mechanisms to control and maintain attitude. The thrust uncertainty may arise from sources such as power supply fluctuations, varying propellant flow rate, faulty thrusters, etc. Thus, an effective control strategy demands a proper modeling of such phenomena. Most importantly, mission requirement, and mass/fuel limitations require a proactive method of control to mitigate the thrust uncertainty and parasitic torque. In providing a method to mitigate the effect of the input uncertainties, spacecraft angular velocity is stabilized through an optimal stochastic control law. This work is presented as an extension to the classical Al'brekht method and ideas from the normal forms theory to solve the Hamilton-Jacobi-Bellman equation associated with a Stochastic Differential Equation. Linear and Nonlinear stochastic control laws along with their performance analysis are presented. [View Full Paper]

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AAS 17-806

A SPARSE COLLOCATION APPROACH FOR OPTIMAL FEEDBACK CONTROL FOR SPACECRAFT ATTITUDE MANEUVERS

Mehrdad Mirzaei,[*] Puneet Singla[†] and Manoranjan Majji[‡]

In this paper, sparse collocation approach is used to develop optimal feedback control laws for spacecraft attitude maneuvers. The effective collocation process is accomplished by utilizing the recently developed Conjugate Unscented Transformation to provide a minimal set of collocation points. In conjunction with the minimal cubature points, an l_1 norm minimization technique is employed to optimally select the appropriate basis functions from a larger complete dictionary of polynomial basis functions. Finite time attitude regulation problem with terminal constraint is considered. Numerical simulations involve asymmetric spacecraft equipped with four reaction wheels. [View Full Paper]

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AAS 17-816

TIME-OPTIMAL REORIENTATION USING NEURAL NETWORK AND PARTICLE SWARM FORMULATION

Ko Basu,[*] Robert G. Melton[†] and Sarah Aguasvivas-Manzano[‡]

A neural network will be developed to supplement a particle swarm algorithm to find near-minimum-time reorientation maneuvers in the presence of path constraints. The method employs a quaternion formulation of the kinematics, using B-splines to represent the quaternions. Dynamic Inversion will be used in the supervised training of the neural network. [View Full Paper]

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AAS 17-819

EFFECTS OF ROTOR GEOMERY ON THE PERFORMANCE OF VIBRATING MASS CONTROL MOMENT GYRPOSCOPES

Ferhat Arberkli,* Burak Akbulut,† Kıvanc Azgin‡ and Ozan Tekinalp§

Elimination of unwanted oscillations on the satellite body that may be caused by the vibrating rotor control moment gyroscopes is addressed. It is mathematically shown that proper rotor inertia selection removes the unwanted oscillations on the output axis of the control moment gyroscope. Simulation results carried out using the ADAMS mechanical modeling and simulation software are given and discussed. [View Full Paper]

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LOW-THRUST TRAJECTORY DESIGN

Session Chair:

Session 4: Jon Sims

The following papers were not available for publication:

AAS 17-729 Paper Withdrawn

AAS 17-803 Paper Withdrawn

AAS 17-609

CHARACTERISTICS OF ENERGY-OPTIMAL SPIRALING LOW-THRUST ESCAPE TRAJECTORIES[*]

Nicholas Bradley[†] and Daniel Grebow[‡]

We present and discuss trajectory characteristics of low-thrust spacecraft thrusting along the instantaneous velocity vector toward escape. The behavior of the osculating eccentricity is examined, in which eccentricity decreases to a minimum before quickly increasing toward escape ($e = 1$). We find that the argument of periapsis replaces true anomaly as the fast time variable, and the spacecraft escapes near an osculating true anomaly of 90 degrees. This behavior was observed by the authors while designing thrusting maneuvers for the Dawn spacecraft. In this paper the dynamical theory governing these observations is discussed and explored with numerical simulations. [View Full Paper]

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SEMI-ANALYTIC PRELIMINARY DESIGN OF LOW-THRUST MISSIONS*

Javier Roa,† Anastassios E. Petropoulos‡ and Ryan S. Park§

Using generalized logarithmic spirals to approximate low-thrust trajectories, a new strategy for the design of low-thrust gravity-assist transfers has been developed. Each transfer leg is defined by a semi-analytic model, and its solution is equivalent to a hybrid Lambert's problem. The method is suitable for approximating both flyby and rendezvous transfer legs. A branch and prune algorithm is used to generate a collection of initial guesses for further optimization. The analytic nature of the low-thrust model simplifies the pruning step, since dynamical and operational constraints (like maximum thrust or total Δv) can be imposed easily. The solutions obtained with the global search algorithm can be post-processed, filtered, and ranked according to various criteria. This is where the versatility of the method resides, because changing the selection criteria does not require a new search. Selected candidates are then optimized further, in order to generate actual low-thrust orbits. Two mission design examples are presented: an asteroid deflection mission using a kinetic impactor, and a rendezvous mission to Jupiter. These examples are used to analyze the convergence of the optimization stage, in particular how far from the optimal solution the initial guesses are. [View Full Paper]

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AAS 17-626

LOW-THRUST TRANSFER DESIGN BASED ON COLLOCATION TECHNIQUES: APPLICATIONS IN THE RESTRICTED THREE-BODY PROBLEM

Robert Pritchett,* Kathleen Howell† and Daniel Grebow‡

Wide-ranging transfer capabilities are necessary to support the development of cislunar space. But, low-thrust transfers between stable periodic orbits are challenging in this regime. Transfer design between such orbits cannot leverage the unstable manifold structures typically employed. Thus, a methodology for constructing these transfers, based on collocation, is demonstrated. Initial guesses comprised of coast arcs along periodic orbits as well as intermediate trajectory arcs from other periodic orbits are converged into feasible transfers and then refined using continuation and optimization strategies. This process applies to various spacecraft configurations and results are validated in a higher-fidelity model. Practical examples demonstrate collocation as a robust approach for computing low-thrust transfers. [View Full Paper]

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AAS 17-727

TRAJECTORY TRACKING GUIDANCE FOR LOW-THRUST GEOSYNCHRONOUS ORBIT INSERTION USING PIECEWISE CONSTANT CONTROL

Ran Zhang[*] and Chao Han[†]

Firstly, an indirect method is applied to optimize the optimal low-thrust transfer problem to geosynchronous orbit. A cubature Kalman filter parameter estimation algorithm is presented to solve the TPBVP, which does not rely on gradient information and is simple, robust. Then a guidance scheme based on tracking the reference orbit is developed to compensate the deviations of the real trajectory. Blending analytic thrust steering laws are used with a few weight coefficients which are determined based on the slope of the reference orbit, thus reducing the computing time significantly onboard the satellite. Finally, the whole trajectory optimization approach and guidance strategy developed in the paper are applied to low thrust GTO-GEO insertion missions. [View Full Paper]

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WAYPOINT-BASED ZEM/ZEV FEEDBACK GUIDANCE: APPLICATIONS TO LOW-THRUST INTERPLANETARY TRANSFER AND ORBIT RAISING

Roberto Furfaro,[*] Giulia Lanave,[†] Francesco Topputo,[‡] Marco Lovera[§] and Richard Linares[**]

Low-thrust guided trajectories for space missions are extremely important for fuel-efficient autonomous space travel. The goal of this paper is to design an optimized, way-point-based, closed-loop solution for low-thrust, long duration orbit transfers. The Zero-Effort-Miss/Zero-Effort-Velocity (ZEM/ZEV) feedback guidance algorithm which has been demonstrated to exhibit great potential for autonomous onboard implementation is applied in a waypoint fashion. Generally, ZEM/ZEV is derived by solving an optimal guidance problem under well-defined assumptions, where the gravitational acceleration is either constant or time-dependent and the thrust/acceleration command is unlimited. If gravity is not constant, the target state is generally achieved in a suboptimal fashion. A way to improve the performances is to divide total trajectory into many segments, and determining with a rigorous optimization method near-optimal waypoints to connect the different segments. Here we consider two possible scenarios, i.e. 1) a low-thrust transfer Earth-Mars and 2) a low-thrust orbit raising from LEO to GEO. For both cases, open-loop energy and fuel-optimal trajectories generated by L. Ferrella and F. Topputo[13] are considered as reference trajectories where a set of arbitrary points are targeted by the ZEM/ZEV guidance in a sequential fashion. An initial parametric study is conducted to evaluate guidance performances as function of the number of the selected waypoints. Subsequently, a global optimization problem, parametrized with the position of the points on the trajectory is solved using a genetic algorithm to determine the minimum set of waypoints necessary for close-to-fuel-optimal waypoint space guidance. The optimization results are compared with the parametric analysis for both scenarios to show that the proposed approach is feasible in achieving quasi-optimal performances even for challenging cases where 500 revolutions are required for low-thrust orbit raising in the Earth gravitational field. Finally, the proposed waypoint-based guidance algorithm is simulated in a more realistic scenarios including perturbing acceleration to verify the robustness of the system via a Monte Carlo analysis. [View Full Paper]

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OPTIMAL POWER PARTITIONING FOR ELECTRIC THRUSTERS

Lorenzo Casalino[*] and Matthew A. Vavrina[†]

High power missions may employ more than one EP thruster and the problem of power partitioning among the thrusters becomes relevant. Space trajectories are controlled by the thrust vector. Optimization consists of finding the optimal control law for thrust magnitude and direction to maximize a specified performance index, while fulfilling given boundary conditions. The paper discusses methods to find the optimal power partitioning among the available thrusters. Different approaches based on indirect methods, direct methods, and evolutionary algorithms are presented. The paper compares the results for test cases related to missions to asteroids, and discusses merits and possible improvements. [View Full Paper]

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EXPLORATION OF LOW-THRUST LOW-ENERGY TRAJECTORIES TO EARTH-MOON HALO ORBITS

Bindu B. Jagannatha,[*] Vishwa Shah,[†] Ryne Beeson[*] and Koki Ho[‡]

Calculating low-energy low-thrust (LE-LT) trajectories that join Earth orbits to lunar orbits in the circular restricted three-body (CR3B) model involves designing the spiral thrust arcs around the primaries on both ends. Existing methods are computationally expensive, involve providing hard-to-obtain initial guesses and do not lend themselves well to quick parametric trade studies. In this paper, two methods are discussed to explore the solution space for designing the Earth-Moon LE-LT transfers and their results compared against each other. The first uses a modified low-thrust feedback control law (Q-law) to design the spiral thrust arcs, while the second patches a tangential thrust arc with a Finite Burn Low Thrust (FBLT) arc to place the spacecraft onto the invariant manifold of the desired halo orbit. [View Full Paper]

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AAS 17-766

IMPROVEMENTS TO SUNDMAN-TRANSFORMED HDDP THROUGH MODIFIED EQUINOCTIAL ELEMENTS

Jonathan D. Aziz* and Daniel J. Scheeres†

Previous efforts addressed the challenge of low-thrust many-revolution trajectory optimization by applying a Sundman transformation to change the independent variable of the spacecraft equations of motion to the eccentric anomaly and performing the optimization with Hybrid Differential Dynamic Programming (HDDP). Improvements to Sundman-transformed HDDP have been realized by representing the spacecraft state with modified equinoctial elements. This paper shows how the modified equinoctial element state representation enters the HDDP algorithm and presents improved results for example transfers from geostationary transfer orbit (GTO) to geosynchronous orbit (GEO).

[View Full Paper]

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AAS 17-832

LOW-THRUST TRAJECTORY OPTIMIZATION WITH SIMPLIFIED SQP ALGORITHM

Nathan L. Parrish* and Daniel J. Scheeres†

The problem of low-thrust trajectory optimization in highly perturbed dynamics is a stressing case for many optimization tools. Highly nonlinear dynamics and continuous thrust are each, separately, non-trivial problems in the field of optimal control, and when combined, the problem is even more difficult. This paper describes a fast, robust method to design a trajectory in the CRTBP (circular restricted three body problem), beginning with no or very little knowledge of the system. The approach is inspired by the SQP (sequential quadratic programming) algorithm, in which a general nonlinear programming problem is solved via a sequence of quadratic problems. A few key simplifications make the algorithm presented fast and robust to initial guess: a quadratic cost function, neglecting the line search step when the solution is known to be far away, judicious use of end-point constraints, and mesh refinement on multiple shooting with fixed-step integration.

[View Full Paper]

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SPACE SITUATIONAL AWARENESS

Session Chair:

Session 5: Rodney Anderson

The following paper was not available for publication:

AAS 17-830 Paper Withdrawn

AAS 17-550

DEBRIS CLOUD CONTAINMENT BOUNDARY ANOMALY

Brian W. Hansen*

A satellite breakup caused by a hypervelocity impact or explosion will create a large cloud of debris particles. One way to represent the evolving boundary of such a cloud is to construct a surface using fragments that all have the maximum breakup spreading speed, but in different directions. It has previously been shown that such a boundary surface will contain any lower-velocity fragments from the breakup event under certain assumptions. This paper investigates an anomaly that arises where those assumptions do not hold, allowing some lower-velocity fragments to escape the boundary at small distances and for small intervals of time. [View Full Paper]

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AAS 17-568

IMPROVED REENTRY PREDICTIONS WITH HIGH FIDELITY MODELS

Eric A. Eiler,[*] Roger C. Thompson[†] and Jason A. Reiter[‡]

Space object reentry predictions are closely tied to uncertainties in multiple key parameters that define the reentering objects and their atmospheric environment. Efforts focusing on the uncertainty surrounding objects' ballistic coefficients are described, with the goal of providing more consistent and accurate lifetime predictions. Times of reentry were derived by high fidelity integration methods. By using an ensemble of runs rather than one single propagation run, trends and variations of multiple reentry prediction times were evaluated. Adjustments to the ballistic coefficient were made to achieve consistent reentry predictions. These predictions are compared to historical reentry data and other methods' predictions. [View Full Paper]

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AAS 17-592

DEBRIS OBJECT ORBIT INITIALIZATION USING THE PROBABILISTIC ADMISSIBLE REGION WITH ASYNCHRONOUS HETEROGENEOUS MEASUREMENTS[*]

Waqar H. Zaidi,[†] W. R. Faber,[†] I. I. Hussein,[†] M. Mercurio,[†] C. W. T. Roscoe,[†] M. P. Wilkins[†] and P. W. Schumacher, Jr.[‡]

One of the most challenging problems in treating space debris is the characterization of the orbit of a newly detected and uncorrelated measurement. The admissible region is defined as the set of physically acceptable orbits (i.e. orbits with negative energies) consistent with one or more measurements of a Resident Space Object (RSO). Given additional constraints on the orbital semi-major axis, eccentricity, etc., the admissible region can be constrained, resulting in the constrained admissible region (CAR). Based on known statistics of the measurement process, one can replace hard constraints with a Probabilistic Admissible Region (PAR), a concept introduced in 2014 as a Monte Carlo uncertainty representation approach using topocentric spherical coordinates. Ultimately, a PAR can be used to initialize a sequential Bayesian estimator and to prioritize orbital propagations in a multiple hypothesis tracking framework such as Finite Set Statistics (FISST). To date, measurements used to build the PAR have been collected concurrently and by the same sensor. In this paper, we allow measurements to have different time stamps. We also allow for non-collocated sensor collections; optical data can be collected by one sensor at a given time and radar data collected by another sensor located elsewhere. We then revisit first principles to link asynchronous optical and radar measurements using both the conservation of specific orbital energy and specific orbital angular momentum. The result from the proposed algorithm is an implicit-Bayesian and non-Gaussian representation of orbital state uncertainty. [View Full Paper]

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AAS 17-600

APPLICATION OF NEW DEBRIS RISK EVOLUTION AND DISPERSAL (DREAD) TOOL TO CHARACTERIZE POST-FRAGMENTATION RISK

Daniel L. Oltrogge[*] and David A. Vallado[†]

The evolution of the debris field generated by an on-orbit explosion or collision fragmentation event is of critical concern to space operators and SSA organizations. Following AGI's recent development of the "Debris Risk Evolution And Dispersal" (DREAD) analysis tool, the authors apply that tool to simulate the effects of collision and explosion events. DREAD modeling of the Iridium/Cosmos collision of 2009 is compared with SSN-observed fragments to verify that the DREAD predictions match well with empirical observations. Additional collision and explosion events are modeled by DREAD to characterize the resulting 3D fragmentation cloud evolution and subsequent risk to all active satellites. Significantly, the DREAD tool facilitates the rapid evaluation of fragmentation downstream collision risk to active satellites as an SSA tool. Additional speed improvements and parallelization techniques to DREAD are also explored.

[View Full Paper]

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AAS 17-639

OPTICAL DATA ASSOCIATION IN A MULTIPLE HYPOTHESIS FRAMEWORK WITH MANEUVERS

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

In Space Situational Awareness (SSA), one may encounter scenarios where the measurements received at a certain time do not correlate to a known Resident Space Object (RSO). Without information that uniquely assigns the measurement to a particular RSO there can be no certainty on the identity of the object. It could be that the measurement was produced by clutter or perhaps a newly birthed RSO. It is also a possibility that the measurement came from a previously known object that maneuvered away from its predicted location. Typically, tracking methods tend to associate uncorrelated measurements to new objects and wait for more information to determine the true RSO population. This can lead to the loss of object custody. The goal of this paper is to utilize a multiple hypothesis framework coupled with some knowledge of RSO maneuvers that allows the user to maintain object custody in scenarios with uncorrelated optical measurement returns. This is achieved by fitting a Fisher-Bingham-Kent type distribution to the hypothesized maneuvers for accurate data association using directional discriminant analysis.

[View Full Paper]

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AAS 17-737

ESTIMATION OF UNTRACKED GEOSYNCHRONOUS POPULATION FROM SHORT-ARC ANGLES-ONLY OBSERVATIONS

Liam M. Healy* and Mark J. Matney†

Telescope observations of the geosynchronous regime will observe two basic types of objects — objects related to geosynchronous earth orbit (GEO) satellites, and objects in highly elliptical geosynchronous transfer orbits (GTO). Because telescopes only measure angular rates, the GTO can occasionally mimic the motion of GEO objects over short arcs. A GEO census based solely on short arc telescope observations may be affected by these geosynchronous mimics. A census that includes multiple angular rates can get an accurate statistical estimate of the GTO population, and that then can be used to correct the estimate of the geosynchronous earth orbit population. [View Full Paper]

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THE PERFORMANCE OF A DIRECTION-BASED BAYESIAN FILTER IN THE ORBITAL TRACKING PROBLEM

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

The space debris tracking problem from a series of angles-only observations can be viewed as an example of Bayesian filtering. Bayesian filtering is easy to implement if the joint distribution of the state vector and the observation vector is normally distributed. Under Keplerian dynamics, the propagation of an initial normally-distributed point cloud does not tend to remain normal in various standard coordinate systems. Hence we propose using an "adapted structural(AST) coordinate system", which preserves approximate normality much more successfully. We analyse the performance of a Bayesian filter in this new coordinate system. [View Full Paper]

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FUSING SURVEY AND FOLLOW-UP FOR SSA SENSOR TASKING

Carolin Frueh*

In the detection and tracking of space objects usually two observation modes are used. Survey for initial detection without a priori information and follow-up to allow for initial orbit determination after the initial detection and for catalog maintenance. In this new framework, sensor tasking is formulated as an optimization problem under realistic conditions. It allows to find the optimal balance between sensor time to detect new objects and to secure and maintain them in the catalog. Probability regions are mapped out. Simulations are used to show the performance of the new optimized framework.

[View Full Paper]

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MANEUVERING DETECTION AND PREDICTION USING INVERSE REINFORCEMENT LEARNING FOR SPACE SITUATIONAL AWARENESS

Richard Linares* and Roberto Furfaro†

This paper uses inverse Reinforcement Learning (RL) to determine the behavior of Space Objects (SOs) by estimating the reward function that an SO is using for control. The approach discussed in this work can be used to analyze maneuvering of SOs from observational data. The inverse RL problem is solved using the feature matching approach. This approach determines the optimal reward function that a SO is using while maneuvering by assuming that the observed trajectories are optimal with respect to the SO's own reward function. This paper utilizes estimated orbital element data to determine the behavior of SOs in a data-driven fashion. Simple proof-of-concept results are shown for a simulation example. [View Full Paper]

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AAS 17-809

CONJUGATE UNSCENTED TRANSFORM BASED JOINT PROBABILITY DATA ASSOCIATION

Nagavenkat Adurthi,[*] Manoranjan Majji,[†]
Utkarsh Ranjan Mishra[‡] and Puneet Singla[§]

The conventional Joint Probabilistic Data Association (JPDA) filtering approach is extended using quadrature based methods to achieve better accuracy and stability. Recently developed conjugate unscented transformation is used in conjunction with the probabilistic data association approach to estimate the association probabilities, while carrying out the state estimation filters for the target candidates of interest. Numerical examples are used to evaluate the utility of the proposed algorithms with Extended Kalman Filter (EKF) based approaches for target association. [View Full Paper]

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TRAJECTORY DESIGN

Session Chair:

Session 6: Roby Wilson

The following paper was not available for publication:

AAS 17-828 Paper Withdrawn

AAS 17-588

A HIGH EARTH, LUNAR RESONANT ORBIT FOR SPACE SCIENCE MISSIONS

Gregory A. Henning,* Randy Persinger† and George R. Ricker‡

To achieve an unobstructed view of space and a stable thermal environment, the Transiting Exoplanet Survey Satellite (TESS) science mission will insert, via lunar gravity assist, into a P/2-HEO Moon-resonant orbit when it launches in 2018. Previous analysis [1] yielded insight into this orbit's behavior, which can be used to optimally select robust mission designs. This paper examines the full orbit trade space to optimize specific launch windows with the lowest possible ΔV and other key mission constraints. Eclipse avoidance is a particularly difficult challenge for this orbit, and a sensitivity study to initial conditions and maneuver errors was performed. [View Full Paper]

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AAS 17-604

PARKER SOLAR PROBE NAVIGATION: ONE YEAR FROM LAUNCH*

Paul F. Thompson,† Troy Goodson,‡ Min-Kun Chung,‡ Drew Jones,§ Eunice Lau,§ Neil Mottinger§ and Powtawche Valerino‡

Parker Solar Probe (PSP) will be the first spacecraft designed to fly deep within the Sun's lower corona and also becoming the fastest spacecraft flown. Launch is scheduled for next year, with a 20-day launch period beginning on 31 July 2018. PSP will be on a ballistic trajectory, requiring seven Venus flybys to progressively lower the perihelion over the seven-year mission. This near-solar environment can be particularly challenging from a spacecraft design as well as a navigation perspective. We discuss an overview of the mission along with some of the particular challenges in navigating PSP.

[View Full Paper]

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AAS 17-631

FLIGHT PATH CONTROL ANALYSIS FOR PARKER SOLAR PROBE

Powtawche N. Valerino,[*] Paul Thompson,[†] Drew Jones,[‡] Troy Goodson,[‡] Min-Kun Chung[‡] and Neil Mottinger[‡]

An unprecedented NASA mission to study the Sun, known as Parker Solar Probe (PSP), is under development. The primary objective of the PSP mission is to gather new data within 10 solar radii of the Sun's center. The purpose of this paper is to review the statistical analysis of trajectory correction maneuvers (TCMs) for PSP's baseline trajectory. The baseline mission includes a total of 42 TCMs that will be accomplished with a monopropellant propulsion system that consists of twelve 4.4 N thrusters. Assuming current navigation models, statistical analyses for each reference trajectory during the 20-day launch period result in a total ΔV99 of less than 100 m/s. [View Full Paper]

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AAS 17-675

SCALING AND BALANCING FOR FASTER TRAJECTORY OPTIMIZATION

I. M. Ross,[*] Q. Gong,[†] M. Karpenko[‡] and R. J. Proulx[§]

It is well-known that proper scaling can increase the efficiency of computational problems. In this paper we define and show that a balancing technique can substantially improve the computational efficiency of trajectory optimization algorithms. We also show that non-canonical scaling and balancing procedures may be used quite effectively to reduce the computational difficulty of some hard problems. These lessons learned have been used for several flight and field operations at NASA and DoD. A surprising aspect of our analysis shows that it may be inadvisable to use auto-scaling procedures employed in some software packages. ***All of our results are agnostic to the specifics of the computational method; hence, they can be used immediately to enhance the utility of any existing algorithm or software***. [View Full Paper]

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AAS 17-694

A DATABASE OF PLANAR AXI-SYMMETRIC PERIODIC ORBITS FOR THE SOLAR SYSTEM

Ricardo L. Restrepo* **and Ryan P. Russell†**

A broad database of planar, axi-symmetric three-body periodic orbits for planets and main planetary satellites in the Solar System is generated and made available online. The database generation is based on a grid search that incorporates a robust differential corrector with a full second-order trust region method. The solutions include periodic orbits in the vicinity of the secondary, orbits that circulate the primary, and more complex solutions that orbit both, allowing for transitions in between. Using a descriptive nomenclature, a detailed characterization of the solutions is presented, including new set of families not previously reported in literature. Emphasis is given on a particular set of solutions that approximate heteroclinic connections between pairs of periodic orbits, providing a framework for efficient trajectory design in multi-body environments. [View Full Paper]

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AAS 17-724

AUTOMATED NODE PLACEMENT CAPABILITY FOR SPACECRAFT TRAJECTORY TARGETING USING HIGHER-ORDER STATE TRANSITION MATRICES

Christopher Spreen* **and Kathleen Howell†**

Targeting and guidance are nontrivial operations, but frequently accomplished by employing discretized representations of a trajectory via nodes along the path, reflecting the full state at specific times. In complex regimes, sensitivity to the start-up arcs, through the node locations, requires experience and knowledge of the dynamical environment for efficient corrections. Building upon previous investigations, an updated, enhanced algorithm is developed to place nodes by leveraging the stability attributes of local Lyapunov exponents. The use of multi-complex numbers for higher-order numerical differentiation aids in the computation of higher-order state transition matrices that expand the capabilities and performance of the node placement algorithm. [View Full Paper]

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AAS 17-749

DESIGN OF LUNAR-GRAVITY-ASSISTED ESCAPE MANEUVERS

Lorenzo Casalino[*] and Gregory Lantoine[†]

Lunar gravity assist is a means to boost the energy and C3 of an escape maneuver. Two approaches are applied and tested for the design of trajectories aimed at Near-Earth asteroids. Maneuvers with two lunar gravity assists are considered and analyzed. Indirect optimization of the heliocentric leg is combined to an approximate analytical treatment of the geocentric phase for short escape maneuvers. The results of pre-computed maps of escape C3 are used for the design of longer sun-perturbed escape sequences. Features are compared and suggestions about a combined use of the approaches are presented. The techniques are efficiently applied to the design of a mission to a near-Earth asteroid.

[View Full Paper]

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AAS 17-776

MCOLL: MONTE COLLOCATION TRAJECTORY DESIGN TOOL

Daniel J. Grebow* **and Thomas A. Pavlak***

In this paper we describe a prototype low-thrust optimization software being developed at JPL. The software tool is based on a collocation algorithm where a trajectory discretization is fitted and adjusted until the underlying dynamics equations of motion are satisfied. The resulting large scale non-linear programming problem may either be optimized with IPOPT or KNITRO. The user specifies path constraints, boundary constraints, and objectives. We describe the collocation algorithm as well as mesh refinement strategies, and apply the software tool to solve various example problems. [View Full Paper]

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AAS 17-790

APPROXIMATE-OPTIMAL FEEDBACK GUIDANCE FOR SOFT LUNAR LANDING USING GAUSSIAN PROCESS REGRESSION

Pradipto Ghosh,* James Woodburn† and Cody Short‡

A recently-developed optimal feedback synthesis method based on Gaussian Process Regression (GPR) is applied to soft lunar landing guidance. GPR is a form of supervised learning technique that is highly useful in constructing surrogate models of unknown functions from input-output training dataset. In this work, GPR has been utilized in capturing the functional relationship between optimal state and control using a pre-generated field of extremals as training data. At each guidance call, when control computation is desired for a newly-sensed state, a new Gaussian process model regressing state and control is created with only a subset of the offline-computed training data, those that are "temporally similar" to the current state. It is argued that this method of sequentially generating approximately optimal controls from a new regression model at each step effectively relaxes the assumption that the underlying map is smooth over the domain of interest. Having designed the GPR-based optimal state-feedback algorithm, its usefulness is assessed by verifying that its application leads to near-optimal trajectories when the lander starts from perturbed initial conditions. A distinctive feature of this work is the realistic quantification of the initial state uncertainty in the form of a full position-velocity estimation error covariance matrix obtained from lunar orbit determination. By randomly sampling states within the extent of this uncertainty, it is shown through numerical experiments that the GPR-based guidance algorithm is highly effective in compensating for imperfectly-known initial conditions of the lander. [View Full Paper]

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TIME-FREE TARGETING FOR DIRECT TRAJECTORY OPTIMIZATION

Nitin Arora,[*] Javier Roa,[†] Anastassios E. Petropoulos[‡] and Nathan Strange[§]

A bounded, time transformation, based on vercosine of the change in eccentric anomaly, is introduced. This transformation, coupled with the F and G functions, explicitly defines the velocity vectors for a pair of position vectors. Using this property, a discretization strategy is formulated where continuous or impulsive thrusting arcs are represented by set of impulses, implicitly realized by maintaining spatial continuity. Time discontinuity is propagated forward and removed at the last grid point either via explicit constraints or a Lambert arc. The trajectory is transformed into a NLP which is solved using existing solvers. Algorithm performance is studied and compared to JPL's Mission Analysis Low-Thrust Optimizer(MALTO). [View Full Paper]

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ADVANCES IN SPACECRAFT DESIGN

Session Chair:

Session 7: Brian Gunter

The following papers were not available for publication:

AAS 17-638 Paper Withdrawn

AAS 17-722 Paper Withdrawn

AAS 17-726 Paper Withdrawn

AAS 17-618

APPLICABILITY OF THE MULTI-SPHERE METHOD TO FLEXIBLE ONE-DIMENSIONAL CONDUCTING STRUCTURES

Jordan Maxwell[*] and Hanspeter Schaub[†]

Electrostatic forces and torques are being exploited in space mission concepts such as charged formation flying, inflatable membrane structures, and space debris mitigation technologies. Electrostatic disturbances are also being studied to predict light-weight space debris trajectories. The analysis of these concepts requires faster-than-realtime electrostatic force and torque modeling. The recently developed Multi-Sphere Method (MSM) approximates the electrostatic field about finite bodies using optimally configured conducting spheres as a base function yielding far-faster than realtime force evaluations. The original MSM development makes the assumption that the space object both has a conducting outer surface and has a rigid shape. This paper investigates the effect of relaxing the rigid shape assumption on model accuracy by studying the charged deformation on a flexible one-dimensional structure. The MSM model is initially developed for a non-deformed state, and then retained as the model geometry is varied. The results show that the impact of the rigid shape approximation is promisingly low, approximating the position of all parts of a 6 cm wire to well within 1 cm. [View Full Paper]

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AAS 17-636

A STABILIZATION METHODOLOGY OF TETHERED SPACE TUG USING ELECTRICAL PROPULSION SYSTEM

Yu Nakajima,[*] Naomi Murakami,[*] Toru Yamamoto[†] and Koji Yamanaka[‡]

This paper proposes a tethered tugging approach for an electrical propulsion system. In general, the thrust force of electrical propulsion is so weak that it has difficulty maintaining tension on the tether. A slack tether adversely affects system stability and poses a higher risk of collision between debris and the tugging satellite. Therefore, this paper proposes an approach that utilizes the gravity gradient torque to stabilize the tethered system by positioning the tugging spacecraft right under the debris on the radial axis. This configuration is stable because gravity gradient torque helps the tether to keep itself aligned on the radial axis. The validity of the proposed approach was verified through dynamics simulation and compared to the general horizontal tugging approach. It is desirable to use soft material since it increases the stability margin compared to the stiff tether. However, the results indicated that the tether longer than 100 m successfully tug the debris stably regardless of its material. [View Full Paper]

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OPTIMAL BLADE PITCH PROFILE FOR AN AUTOROTATIVE ENTRY VEHICLE

Dario Modenini,[*] Marco Zannoni[*] and Paolo Tortora[†]

We consider the Entry Descent and Landing problem for a vehicle equipped with an unpowered rotary decelerator, having Mars as planetary target. We aim at computing an optimal blade pitch profile to maximize the overall decelerating effect exerted by the rotor. To this end, we set up an optimization problem with one state variable (the altitude) specified at an unknown terminal time, with the landing speed as the objective function to be minimized. Results show the effectiveness of the proposed approach in reducing the terminal velocity with respect to what achieved when using simple constant pitch settings, by more than 10 m/s. [View Full Paper]

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AAS 17-725

DESIGN OF OBSTACLE AVOIDANCE IN HIGH TRACKING ACCURACY FOR SPATIAL MANIPULATOR

Ting-ting Sui,* Xiao Ma,† Jian Guo† and Jun Guo‡

Aiming at the shortage of traditional obstacle avoidance algorithm, an obstacle avoidance algorithm based on spatial operator algebra which applicable to multiple obstacles is put forward in this paper; the complexity of Jacobian is greatly simplified by the algorithm based on Spatial operator algebra (SOA), and the minimum distance between each obstacle and manipulator is calculated by the algorithm, and transformed to the escape speed of each bar by the Jacobian transpose matrix. With the gradient projection method, the escape speed of each bar is used to obtain the joint velocity related. At the same time, with the position tracking control of the end, the obstacle avoidance control could be obtained, which can ensure that the efficiency of calculation is O(N) and accuracy of position the end reach is high, based on efficient modeling method in kinematics and dynamics. A manipulator with 7-DOF is used in the simulation whose results verify the correctness and effectiveness of the algorithm. [View Full Paper]

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AAS 17-734

LABORATORY EXPERIMENTS ON THE CAPTURE OF A TUMBLING OBJECT BY A SPACECRAFT-MANIPULATOR SYSTEM USING A CONVEX-PROGRAMMING-BASED GUIDANCE

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

An onboard implementable optimization-based guidance approach for the capture of tumbling objects by spacecraft equipped with a robotic manipulator is demonstrated on a hardware-in-the-loop test bed. The experimental demonstration is conducted using spacecraft simulators operating on the reduced-gravity and drag-free dynamic environment provided by a planar air bearing test bed. The proposed approach uses a two-step sequential convex programming procedure introduced in an earlier work. The first step optimizes the center-of-mass translation while the second step optimizes the motion of the multibody system around its center-of-mass. A sequential convex programming procedure is used on both optimization steps, casting the original optimization problem into a collection of convex programming problems. A proof of convergence is introduced here for the system-wide translation in the presence of non-convex keep-out zone constraints. These experiments significantly advance the demonstrated state-of-the-art for robotic capture maneuvers. [View Full Paper]

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DYNAMIC MODELING OF FOLDED DEPLOYABLE SPACE STRUCTURES WITH FLEXIBLE HINGES

JoAnna Fulton[*] and Hanspeter Schaub[†]

A modeling approach for capturing the three-dimensional deployment dynamics of complex folded deployable structures with flexible hinges on spacecraft is developed. This paper provides an initial investigation on how to model flexible hinges that connect rigid panels. Such hinges are emerging as a promising use of composite materials to create novel folded structures. The nonlinear multi-body dynamics is studied and described using an energy-based approach and parameterizations developed for attitude dynamics and control to better understand how the structure's motion affects the spacecraft. While this study assumes a simple hinge-response behavior, the dynamical formulation is general enough to substitute experimentally derived response functions in future efforts.

[View Full Paper]

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AAS 17-797

CISLUNAR MISSION DESIGN FOR LOW-THRUST SMALLSATS

**Vishwa Shah,[*] Joshua Aurich,[*] Ryne Beeson,[†]
Donald Ellison[†] and Kaushik Ponnapalli[‡]**

The continued development of small satellite technology has expanded the menu of missions that these craft could potentially carry out to Lagrange points, the Moon, and even near Earth objects. Several small sats will be launched as secondary payloads on Explorer Mission 1 (EM-1) in 2018, and will explore different science objectives in the cislunar region. However, due to their limited power and propulsion capabilities as well as a high velocity release condition from EM-1, designing feasible solutions is a challenging task. In addition, launch conditions and spacecraft parameters have larger variability and change more often during the mission design and production phases in comparison to larger explorer and flagship type missions; driving the need for an efficient and robust automated tool set that enables rapid prototyping of mission concepts. In this paper, we apply a hybrid optimal control framework that leverages dynamical structures found in multi-body regimes to explore low-energy solutions to EM-1 small satellite type missions. The hybrid optimal control framework supports a flexible and automated approach that still allows full user guidance via appropriately formed objectives and constraints, while enabling a search of the design space in an intelligent manner that can yield non-intuitive results. [View Full Paper]

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AAS 17-824

STABILITY ANALYSIS OF GENERALIZED SAIL DYNAMICS MODEL

Go Ono,[*] Shota Kikuchi[†] and Yuichi Tsuda[‡]

This paper addresses a stability analysis for an attitude model called the Generalized Sail Dynamics Model, which describes attitude dynamics of a momentum-biased spacecraft with arbitrary shape and optical reflectance properties. In the model, there is a coupling between internal angular momentum of a spacecraft and solar radiation pressure (SRP) torque. This results in passive sun-tracking attitude motion, and therefore, stability is particularly important. In this paper, general stability conditions are derived analytically by eigenvalue and phase plane analyses, and are verified with a numerical analysis by computing SRP torque acting on a spacecraft. The results provide an insight into spacecraft design for stable attitude motion. [View Full Paper]

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COLLISION AVOIDANCE

Session Chair:

Session 9: Carolin Frueh

The following paper was not available for publication:

AAS 17-782 Paper Withdrawn

AAS 17-556

A MONTE-CARLO STUDY OF CONJUNCTION ANALYSIS USING PARAMAT

Darrel J. Conway[*]

This study uses the numerical engine in the General Mission Analysis Tool, driven from the parallel processing tool Paramat, to model a conjunction analysis between two spacecraft on eccentric, nearly coincident trajectories. The spacecraft initial states are separated by 92 meters, and come to within about 9 meters of each other two days later when propagated on their nominal trajectories. The covariance matrix of the initial state data is used to perturb each spacecraft, and the spacecraft are then propagated to the point of closest approach. A Monte Carlo study of the close approach separations and the probability of collision is presented using these perturbed states. The modeling is performed using several different force models, and the results of each configuration are shown to be similar. Two additional test cases are also briefly examined. Performance data for the study is presented, along with a discussion of the methodology and of the tools used.

[View Full Paper]

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AAS 17-559

CONJUNCTION ASSESSMENT SCREENING VOLUME SIZING AND EVENT FILTERING IN LIGHT OF NATURAL CONJUNCTION EVENT DEVELOPMENT BEHAVIORS

M. D. Hejduk[*] and D. A. Pachura[†]

Conjunction Assessment screening volumes used in the protection of NASA satellites are constructed as geometric volumes about these satellites, of a size expected to capture a certain percentage of the serious conjunction events by a certain time before closest approach. However, the analyses that established these sizes were grounded on covariance-based projections rather than empirical screening results, did not tailor the volume sizes to ensure operational actionability of those results, and did not consider the adjunct ability to produce data that could provide prevenient assistance for maneuver planning. The present study effort seeks to reconsider these questions based on a six-month dataset of empirical screening results using an extremely large screening volume. The results, pursued here for a highly-populated orbit regime near 700km altitude, identify theoretical limits of screening volume performance, explore volume configuration to facilitate both maneuver remediation planning as well as basic asset protection, and recommend sizing principles that maximize volume performance while minimizing the capture of "chaff" conjunctions that are unlikely ever to become serious events. [View Full Paper]

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REMEDIATING NON-POSITIVE DEFINITE STATE COVARIANCES FOR COLLISION PROBABILITY ESTIMATION

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

The NASA Conjunction Assessment Risk Analysis team estimates the probability of collision (P_c) for a set of Earth-orbiting satellites. The P_c estimation software processes satellite position+velocity states and their associated covariance matrices. On occasion, the software encounters *non-positive definite* (NPD) state covariances, which can adversely affect or prevent the P_c estimation process. Interpolation inaccuracies appear to account for the majority of such covariances, although other mechanisms contribute also. This paper investigates the origin of NPD state covariance matrices, three different methods for remediating these covariances when and if necessary, and the associated effects on the P_c estimation process. [View Full Paper]

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AAS 17-582

STOCHASTIC DYNAMICS OF AND COLLISION PREDICTION FOR LOW ALTITUDE EARTH SATELLITES

Adam T. Rich,* Kenneth J. Stuart* and William E. Wiesel†

Air drag $B*$ factors from earth satellite element sets often show the characteristic near Gaussian distribution and autocorrelation exponential decay typical of a first order Gauss-Markov process. Assuming the "most current" set of orbital elements are correct, earlier elements can be used to construct covariance matrices as a function of prediction time into the future. If resolved in cylindrical orbit frame coordinates, these are remarkably structured, essentially showing only in-track error growth. Often the in-track position covariance element growth follows a fourth power in time rule, and is apparently forced by the uncertainty in the air drag factor. Realizing that almost all error growth under the SGP4 model is in track, the Cosmos 2251 / Iridium 33 event is reexamined. While a collision prediction from the last elements shows a minimum miss distance of about 700 meters, those same elements show a closest approach distance of the *orbits* of only 32 meters. Given large in-track uncertainty, minimum orbit separation may be a much more reliable metric for maneuver decisions. [View Full Paper]

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AAS 17-590

OPTIMAL COLLISION AVOIDANCE MANEUVERS FOR SPACECRAFT PROXIMITY OPERATIONS VIA DISCRETE-TIME HAMILTON-JACOBI THEORY

Kwangwon Lee,[*] Youngho Eun[†] and Chandeok Park[‡]

This study presents a sub-optimal control algorithm that implements real-time collision avoidance maneuvers for spacecraft in proximity operations. The penalty function for avoiding collision with an obstacle is first incorporated into the performance index of a typical optimal tracking problem in a discrete-time do-main. Then, the infinite-horizon control law is derived by employing generating functions based on the discrete-time Hamilton-Jacobi theory without initial guess and iterative procedure. The derived control law, which is an explicit function of the states of desired solution and obstacles, allows us to avoid collision in real-time. The proposed approach has advantages over the previous optimal collision avoidance approaches requiring repetitive procedure and initial guess, and/or trajectories of obstacles to be known a priori. Numerical simulations demonstrate that the proposed algorithm is suitable for implementing optimal collision-free transfers in real-time. [View Full Paper]

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RELEVANCE OF THE AMERICAN STATISTICAL ASSOCIATION'S WARNING ON *p*-VALUES FOR CONJUNCTION ASSESSMENT

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On March 7, 2016, the American Statistical Association issued an editorial paper on the "context, process, and purpose of *p*-values." According to the paper, "the statement articulates in non-technical terms a few select principles that could improve the conduct or interpretation of quantitative science, according to widespread consensus in the statistical community." These principles would appear to have some relevance to the spacecraft conjunction assessment community. [View Full Paper]

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AAS 17-650

THE EVOLUTION OF SECONDARY OBJECT POSITION IN 18SCS CONJUNCTION DATA MESSAGES

Barbara Manganis Braun[*]

Satellite owners evaluate conjunctions with on-orbit objects every day, and rely on conjunction data messages produced by the 18th Space Control Squadron (formerly known as JSpOC) to make maneuver decisions. Each conjunction assessment relies on predicting the position of both the primary and secondary object at the time of closest approach. This paper examines the position predictions of all secondary objects conjuncting with three primary satellites over a six-month period. The data illustrates interesting characteristics of 18SCS secondary object position prediction, including the differences between orbital regimes, the impact of increased tracking, and the prevalence of repeating conjunctions. [View Full Paper]

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AAS 17-703

PROBABILITY OF COLLISION ESTIMATION AND OPTIMIZATION UNDER UNCERTAINTY UTILIZING SEPARATED REPRESENTATIONS

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

In crowded orbit regimes due to debris or inoperable satellites, operators of spacecraft must confront the possibility of a conjunction with another space object and decide whether the risk should be mitigated or accepted. Often, the decision to maneuver or not is decided by the probability of collision. This paper presents Separated representations for estimating the probability of collision between two satellites, and the design of a collision avoidance maneuver while accounting for propagated uncertainty. Separated representations is a polynomial surrogate method that has a computation cost largely linear with respect to dimension, allowing the consideration of high-dimension stochastic systems. [View Full Paper]

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PLANETARY EXPLORATION

Session Chair:

Session 10: Nitin Arora

AAS 17-608

ONE CLASS OF IO-EUROPA-GANYMEDE TRIPLE CYCLERS

Sonia Hernandez,[*] Drew R. Jones[*] and Mark Jesick[*]

Ballistic cycler trajectories that repeatedly encounter the Jovian moons Ganymede, Europa, and Io are investigated. The 1:2:4 orbital resonance among these moons allows for trajectories that periodically fly by the three bodies, and under idealized assumptions repeat indefinitely. An initial search method is implemented to determine if the location of the moons in a specific geometry can give way to a possible cycler. Lambert's problem is then solved to determine the legs connecting consecutive encounters, allowing a maneuver at periapsis of the encounter if necessary. Families of solutions are classified by synodic period, and conversion to high fidelity model is outlined. [View Full Paper]

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AAS 17-651

A TOOL FOR IDENTIFYING KEY GRAVITY-ASSIST TRAJECTORIES FROM BROAD SEARCH RESULTS

James W. Moore,* Kyle M. Hughes,† Alec J. Mudek‡ and James M. Longuski§

A tool is presented that identifies desirable trajectory candidates from among tens of thousands of gravity-assist trajectories. A broad trajectory search technique creates an exhaustive set of possible trajectories to a given planet. From this dataset, our tool reveals candidate trajectories with user-defined characteristics. Typical discriminating characteristics are launch V-infinity, time-of-flight, and delivered mass. Mission planners evaluate and plot interesting trajectories from within the tool. Our tool generates catalogs of selected trajectories for further evaluation with higher-fidelity trajectory solvers. This paper outlines the key features of the tool and gives examples of typical analyses.

[View Full Paper]

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AAS 17-696

PRACTICAL METHODOLOGIES FOR LOW DELTA-V PENALTY, ON-TIME DEPARTURES TO ARBITRARY INTERPLANETARY DESTINATIONS FROM A MEDIUM-INCLINATION LOW-EARTH ORBIT DEPOT

Michel Loucks,[*] Jonathan Goff[†] and John Carrico[‡]

The authors present a 3-burn injection method that enables manned and robotic spacecraft to depart for interplanetary destinations from a Low-Earth Orbit propellant depot with only minor ΔV penalties. In this paper, the authors discuss related injection methodologies; illustrate the underlying concept behind this three-burn injection method; discuss implications of using this method, including potential mission safety benefits; and present some details on estimates of the worst-case ΔV penalty for performing this sort of departure maneuver, compared with a traditional one-burn departure from a LEO parking orbit.
[View Full Paper]

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AAS 17-699

MISSION DESIGN FOR THE EMIRATES MARS MISSION

**Jeffrey S. Parker,*
Omar Hussain,† Nathan Parrish‡ and Michel Loucks‡**

The United Arab Emirates is launching the Emirates Mars Mission (EMM) to Mars in 2020 to explore the atmospheric dynamics of Mars on a global, diurnal, sub-seasonal scale. The mission design involves a Type I transfer to Mars, coordinated with many other simultaneous Mars missions, most of whom share the same network of ground tracking stations. The Mars Orbit Insertion places the EMM Observatory, *Amal*, into a very large, elliptical capture orbit. Three Transition to Science Maneuvers are optimized under uncertainty to transfer the spacecraft into a unique 20,000 km x 43,000 km, ideally shaped and oriented to achieve the EMM science objectives. [View Full Paper]

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AAS 17-708

ROBUST MINIATURE PROBES FOR EXPANDED ATMOSPHERIC PLANETARY EXPLORATION

Eiji Shibata*

For future atmospheric planetary exploration, a robust miniature probe can be used to provide additional in-situ measurements, while keeping consequential costs and risks low. These probes take advantage of recently-developed technologies in the small satellite field and apply those technologies to atmospheric probe entry. These probes arrive at an atmospheric body with a cruise stage—all delivered by a larger, primary spacecraft. The cruise stage serves to provide additional pointing accuracy for entry without using the fuel onboard the primary spacecraft. [View Full Paper]

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BALLISTIC AND HIGH-THRUST TRAJECTORY OPTIONS TO URANUS CONSIDERING 50 YEARS OF LAUNCH DATES

Alec J. Mudek,* James W. Moore,† Kyle M. Hughes,‡
Sarag J. Saikia§ and James M. Longuski**

Given that Uranus is a high-priority scientific target, ballistic and chemical trajectory options to the ice giant are investigated for launch dates spanning 50 years. A total of 89 distinct gravity-assist paths are considered for ballistic trajectories and—for cases where no ballistic trajectories exist—a single deep space maneuver (DSM) up to 3 km/s may be applied. For each launch year, the most desirable trajectory is identified and cataloged based on time of flight (up to 15 years), total ΔV cost (DSM and capture maneuver), arrival V_∞, and delivered payload. The Atlas V 551, Delta IV Heavy, and SLS Block 1B are considered as launch vehicles. The trajectories are found using a patched-conic propagator with an analytical ephemeris model. Jupiter is unavailable as a gravity-assist body until the end of the 2020s but alternative gravity-assist paths exist, providing feasible trajectories even in years when Jupiter is not available. A probe-and-orbiter mission to Uranus is feasible with the Delta IV Heavy with approximately 13-year flight times and with the Atlas V 551 with approximately 14.5-year flight times. Using the SLS Block 1B, the flight times are around 10 to 11 years but can be as low as 7.5. [View Full Paper]

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LOW-COST OPPORTUNITY FOR MULTIPLE TRANS-NEPTUNIAN OBJECT RENDEZVOUS AND ORBITAL CAPTURE

Glen E. Costigan,[*] Brenton W. Ho,[*] Nicole Nutter,[*] Katherine Stamper[*] and James E. Lyne[†]

New Horizons remains the only spacecraft ever to visit a trans-Neptunian object and while the probe will continue to intercept more objects in the Kuiper Belt, the outer reaches of the solar system remain woefully underexplored. The mission proposed herein allows three separate *New Horizons*-type spacecraft to reach three trans-Neptunian object systems with the use of a single launch vehicle. This was accomplished by performing a ΔVEGA maneuver at the beginning of the trajectories which reduced the required launch C3 from over 100 m^2/s^2 to under 30 m^2/s^2. Two of the proposed target systems, binary dwarf planet 2002 UX25 and binary cubewano system 1998 WW31, intercept their assigned spacecraft 17.3 and 25.3 years after launch, respectively. The relative velocities between the spacecraft and the TNO systems were constrained to allow for meaningful data collection by the onboard instrumentation suites. The third spacecraft is equipped with a high-thrust engine which enables it to capture into orbit around the trinary TNO system 1999 TC36 26.3 years after launch. [View Full Paper]

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ENCELADUS SAMPLE RETURN MISSION

Rekesh M. Ali,[*] Andrew S. Bishop,[*] Braxton Brakefield,[*] Shelby Honaker,[*] Brier Taylor[*] and James E. Lyne[†]

The Cassini mission has confirmed that Enceladus has a subsurface liquid ocean and hydrothermal vents that may support life, as well as geysers that eject water from beneath the frozen surface into space. This provides an unusual opportunity to sample the interior without necessitating a landing. In this study, a novel, flyby sample return mission is examined, using a previously published free-return interplanetary trajectory. We propose the use of multiple small pods that would be released from a carrier bus prior to the Enceladus encounter. These pods would collect ejected material during flyby and would each return to Earth independently, thereby reducing or eliminating the possibility of a single point failure after the pod release. The pods would enter Earth's atmosphere at a speed of 15.7 km/s, by far the fastest Earth entry to date. The small size of the pods tends to reduce their ballistic coefficient, thereby making such a high entry speed potentially feasible. [View Full Paper]

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AAS 17-847

OPTIMIZING PARKING ORBITS FOR ROUNDTRIP MARS MISSIONS

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

A roundtrip Mars mission presents many challenges to the design of a transportation system and requires a series of orbital maneuvers within Mars vicinity to capture, reorient, and then return the spacecraft back to Earth. The selection of a Mars parking orbit is crucial to the mission design; not only can the parking orbit choice drastically impact the ΔV requirements of these maneuvers but also it must be properly aligned to target desired surface or orbital destinations. This paper presents a method that can optimize the Mars parking orbits given the arrival and departure conditions from heliocentric trajectories, and it can also enforce constraints on the parking orbits to satisfy other architecture design requirements such as co-planar sub-periapsis descent to planned landing sites, due east or co-planar ascent back to the parking orbit, or low cost transfers to and from Phobos and Deimos. [View Full Paper]

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AAS 17-849

PATH PLANNING TO A REACHABLE STATE USING INVERSE DYNAMICS AND MINIMUM CONTROL EFFORT BASED NAVIGATION FUNCTIONS

Paul Quillen,* Josué Muñoz† and Kamesh Subbarao‡

The purpose of this paper is to present a new path-planning algorithm for planetary exploration rovers that will guide the vehicle safely to a reachable state. In particular, this work will make use of a special class of artificial potential functions called navigation functions which are guaranteed to be free of local minimum. The construction of the navigation functions in this work is motivated by the grid-based wavefront expansion method but differs in that the contour levels are defined in terms of the control effort of the system. Two new methods will be introduced in this paper for defining the navigation function. The first method will generate a minimum control effort path plan and the second method will be based on an inverse dynamics approach. Each of the control effort based methods will generate a path plan that will guide the rover's approach towards an objective reachable state. Finally, a stable backstepping controller is implemented to track a trajectory defined along the path plan to the rover's objective. [View Full Paper]

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ATTITUDE ESTIMATION

Session Chair:

Session 11: Ryan Russell

The following paper was not available for publication:

AAS 17-845 Paper Withdrawn

AAS 17-554

TREATMENT OF MEASUREMENT VARIANCE FOR STAR TRACKER-BASED ATTITUDE ESTIMATION

Erik A Hogan[*] and Byoungsam (Andy) Woo[†]

In this paper, proper treatment of measurement variance for star tracker-based attitude estimation routines is considered. Specifically, a modified Rodrigues parameter (MRP) additive extended Kalman filter (EKF) is used in combination with one or more star trackers and a rate gyro to perform attitude estimation. In prior work, the differences between noise characteristics about the three star tracker sensing axes are not considered, and the effects of measurement latency are not addressed. Considering these effects, as well as star tracker alignments, the correct way to compute the measurement variance for the measurement residuals in the additive MRP EKF is provided. The results illustrate the improved performance gained over classical results and highlight the importance of properly calculating measurement variance, especially for agile spacecraft.

[View Full Paper]

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AAS 17-591

TUNING THE SOLAR DYNAMICS OBSERVATORY ONBOARD KALMAN FILTER

Julie Halverson (formerly Thienel),[*] Rick Harman,[†] Russell Carpenter[‡] and Devin Poland[§]

The Solar Dynamics Observatory (SDO) was launched in 2010. SDO is a sun-pointing semi-autonomous spacecraft in a geosynchronous orbit that allows nearly continuous observations of the sun. SDO is equipped with coarse sun sensors, two star trackers, a digital sun sensor, and three two-axis inertial reference units (IRU). The IRUs are temperature sensitive and were designed to operate in a stable thermal environment. Due to battery degradation concerns the IRU heaters were not used on SDO and the onboard filter was tuned to accommodate the noisier IRU data. Since launch currents have increased on two IRUs, one had to eventually be powered off. Recent ground tests on a battery similar to SDO's indicated the heaters would have negligible impact on battery degradation, so in 2016 a decision was made to turn the heaters on. This paper presents the analysis and results of updating the SDO filter tuning parameters with the IRUs now operating in their intended thermal environment. [View Full Paper]

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AAS 17-637

ADVANCED ATTITUDE DETERMINATION ALGORITHM FOR ARASE: PRELIMINARY MISSION EXPERIENCE

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

JAXA's ERG (Exploration of Energization and Radiation in Geospace) Spacecraft, which is nicknamed Arase, was launched on 20 December 2016. Arase is a spin-stabilized and Sun-oriented spacecraft. Its mission is exploring how relativistic electrons in the radiation belts are generated during space storms. Two different on-ground attitude determination algorithms have been designed for the mission: a conventional straightforward algorithm that inherits from old missions and an advanced new algorithm. This paper discusses the design of the advanced attitude determination algorithm and presents the preliminary attitude estimation results for the spacecraft that were obtained after the launch. Results are presented along with the encountered challenges and suggested solutions. [View Full Paper]

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AAS 17-673

SPACECRAFT ATTITUDE ESTIMATION USING UNSCENTED KALMAN FILTERS, REGULARIZED PARTICLE FILTER AND EXTENDED H_∞ FILTER

William R. Silva,[*] Roberta V. Garcia,[†] Hélio K. Kuga[‡] and Maria C. Zanardi[§]

In this work, the attitude determination and the gyros drift estimation will be described for nonlinear systems using the Extended Kalman Filter (EKF), Extended H_∞ Filter ($EH_\infty F$), Second-Order Extended H_∞ Filter ($SOEH_\infty F$), Unscented Kalman Filter (UKF) and Regularized Particle Filter (RPF). An analysis of these estimation methods will be done, verifying which of them present better precision in such study. The attitude model is described by quaternions and the attitude sensors available are two DSS (Digital Sun Sensors), two IRES (Infrared Earth Sensor), and one triad of mechanical gyros. The application uses the simulated measurement data for orbit and attitude of the CBERS-2 (China Brazil Earth Resources Satellite) which has polar sun-synchronous orbit with an altitude of 778km, making about 14 revolutions per day. In this orbit, the satellite crosses the equator line always at the same local time, around 10:30 am. This dynamics allows the same conditions of solar illumination to be obtained during the acquisition of images. The simulated measurements of the CBERS-2 were provided by the inhouse package PROPAT, a Satellite Attitude and Orbit Toolbox for Matlab. The results in this work show that one can reach accuracies in attitude determination within the prescribed requirements, besides providing estimates of the gyro drifts which can be further used to enhance the gyro error model. [View Full Paper]

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SPACECRAFT HIGH ACCURACY ATTITUDE ESTIMATION: PERFORMANCE COMPARISON OF QUATERNION BASED EKF AND UF

Divya Bhatia[*]

Demand for high accuracy attitude estimation of the order better than tens of milli-arcsec is growing for the future spacecraft missions. To this end, this paper compares the performance characteristics of quaternion based Extended Kalman filter (EKF) and Unscented filter (UF) for three axes attitude estimation of IRASSI spacecraft. Quaternions are appealing parameters for attitude representation owing to their bilinear kinematic equation and singularity-free property. Performance parameters compared are the pointing accuracy, robustness and convergence of both the filters for the fusion of a high accuracy three-axis gyroscope and two simultaneously operating high accuracy star trackers.

[View Full Paper]

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AAS 17-767

INVERSE DYNAMICS PARTICLE SWARM OPTIMIZATION APPLIED TO BOLZA PROBLEMS

Dario Spiller,* Robert G. Melton† and Fabio Curti‡

The Inverse-dynamics Particle Swarm Optimization has already been successfully applied to several minimum-time problems. This numerical technique based on swarm intelligence is applied to solve optimal control problems formulated with the differentially flat approach. The advantages of this method lie in the global search ability of the optimizer and the reduction of the independent functions due to the exploitation of the differential flatness. However, it is known that optimal control problems formulated with either differential inclusion or differential flatness can lead to nonconvex problems with undesirable numerical properties. This paper in intended to show that, considering difficult problems with nonconvex state constraints and nonconvex cost functions, the proposed numerical technique can lead to satisfactory near-optimal solutions. Minimum-time, minimum-energy and minimum-effort maneuvers are addressed considering a constrained slew-maneuver as a test case. [View Full Paper]

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ORBITAL DYNAMICS

Session Chair:

Session 12: Angela Bowes

AAS 17-553

A KAM TORI ALGORITHM FOR EARTH SATELLITE ORBITS

William E. Wiesel*

This paper offers a new approach for constructing Kolmogorov - Arnold - Moser (KAM) tori for orbits in the full potential for a non-spherical planet. The Hamilton - Jacobi equation is solved numerically by a Newton-Rhapson iteration, achieving convergence to machine precision, and still retaining literal variable dependence. Similar iteration methods allow correcting the orbital frequencies, and permit the calculation of the state transition matrix for the full problem. Some initial numerical examples are offered.

[View Full Paper]

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AAS 17-572

RELATIVE EQUILIBRIA FOR THE ROTO-ORBITAL DYNAMICS OF A RIGID BODY AROUND A SPHERE

Francisco Crespo* **and Sebastián Ferrer†**

We study the roto-orbital motion of an arbitrary rigid body and a sphere, which is assumed to be much more massive than the triaxial body. The associated dynamics to this system, which consists of a normalized Hamiltonian with respect to the fast angles (partial averaging), is investigated making use of variables referred to the total angular momentum. The first order approximation of this model is integrable. We carry out the analysis of the relative equilibria, which hinges principally in the dihedral angle between the orbital and rotational planes and the ratio among the momenta $\rho = (B - A)/(2C - B - A)$. In particular, the dynamics of the body frame, though formally given by the classical Euler equations, it experiences changes of stability in the principal directions related to the roto-orbital coupling. We find a new type of special-shaped bodies leading to a family of relative equilibria connected to the unstable equilibria of the free rigid body.

[View Full Paper]

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AAS 17-579

APPLICATION OF MULTI-HYPOTHESIS SEQUENTIAL MONTE CARLO FOR BREAKUP ANALYSIS*

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

As more objects are launched into space, the potential for breakup events and space object collisions is ever increasing. These events create large clouds of debris that are extremely hazardous to space operations. Providing timely, accurate, and statistically meaningful Space Situational Awareness (SSA) data is crucial in order to protect assets and operations in space. The space object tracking problem, in general, is nonlinear in both state dynamics and observations, making it ill-suited to linear filtering techniques such as the Kalman filter. Additionally, given the multi-object, multi-scenario nature of the problem, space situational awareness requires multi-hypothesis tracking and management that is combinatorially challenging in nature. In practice, it is often seen that assumptions of underlying linearity and/or Gaussianity are used to provide tractable solutions to the multiple space object tracking problem. However, these assumptions are, at times, detrimental to tracking data and provide statistically inconsistent solutions. The goal of this paper is to provide a tractable solution to the multiple space object tracking problem that is statistically rigorous in the fact that simplifying assumptions of the underlying probability density function are relaxed and heuristic methods for hypothesis management are avoided. This is done by implementing Sequential Monte Carlo (SMC) methods for both nonlinear filtering as well as hypothesis management. This paper presents an expansion from a single birthed space object tracking framework to multiple space object tracking with applications to space debris and the tracking of Resident Space Object (RSO) breakup events. [View Full Paper]

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AAS 17-581

A METHODOLOGY FOR REDUCED ORDER MODELING AND CALIBRATION OF THE UPPER ATMOSPHERE

Piyush M. Mehta* **and Richard Linares†**

Atmospheric drag is the largest source of uncertainty in accurately predicting the orbit of satellites in low Earth orbit (LEO). Accurately predicting drag for objects that traverse LEO is critical to Space Situational Awareness. Atmospheric models used for orbital drag calculations can be characterized either as empirical or physics-based (first principles based). Empirical models are fast to evaluate but offer limited real-time predictive/forecasting ability, while physics-based models offer greater predictive/forecasting ability but require dedicated parallel computational resources. Also, calibration with accurate data is required for either type of models. This paper presents a new methodology based on proper orthrogonal decomposition (POD) towards development of a quasi-physical, predictive, reduced order model that combines the speed of empirical and the predictive/forecasting capabilities of physics-based models. The methodology is developed to reduce the high-dimensionality of physics-based models while maintaining its capabilities. We develop the methodology using the Naval Research Lab's MSIS model and show that the diurnal and seasonal variations can be captured using a small number of modes and parameters. We also present calibration of the reduced order model using the CHAMP and GRACE accelerometer-derived densities. Results show that the method performs well for modeling and calibration of the upper atmosphere. [View Full Paper]

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A NEW CONCEPT OF STABILITY IN ORBIT PROPAGATION, USEFUL FOR QUANTIFYING NUMERICAL ERRORS

Javier Roa,* Hodei Urrutxua† and Jesús Peláez‡

We present the concept of topological stability in the numerical propagation of orbits, and show how it results in a useful new method for measuring the global numerical error of an orbit propagation. The concept applies to any problem in orbital dynamics. Moreover, it can be extended to any three-dimensional system of differential equations of second order. In order to assess the topological stability of a given integration a special metric is introduced, which can be used to estimate the numerical errors robustly. The method is particularly well suited for dealing with strongly perturbed and chaotic systems. The construction is based on the constraint imposed by the Hopf map that supports the Kustaanheimo-Stiefel transformation. Generic concepts of stability are translated to KS space.

[View Full Paper]

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ORBITAL LIFETIME ANDCOLLISION RISK REDUCTION FOR TUNDRA DISPOSAL ORBITS

Alan B. Jenkin,* John P. McVey,† James R. Wilson,‡ Isabella Acevedo-Rodriguez§ and Marlon E. Sorge**

Tundra orbits are high-inclination, moderately eccentric, 24-hour period orbits. A previous paper by the authors showed that eccentricity excursions due to luni-solar gravity can be used to reduce disposal orbit lifetime and long-term collision risk. This paper presents results of a more extensive follow-on study. TRACE propagations were performed to determine variation of orbital lifetime with initial epoch and orbital parameters. The Aerospace Debris Environment Projection Tool (ADEPT) suite was used to determine collision risk with inactive objects and geosynchronous (GEO) operational satellites. Results show that, when orbital lifetime is reduced below 200 years, collision probability with both inactive objects and GEO operational satellites is well below the 0.001 threshold in U.S. orbital debris mitigation rules and well below the collision risk for near-GEO disposal orbits and 25-year lifetime low Earth orbits (LEO). The maximum effective total time spent by a Tundra satellite in LEO is well below the recommended limit of 25 years in international guidelines, and the maximum effective total time spent in the GEO altitude range is well below the orbital lifetime. The use of a Tundra disposal orbit would avoid substantial propellant cost required to move to a disposal orbit that clears GEO. Substantial additional propellant can be saved by allowing Tundra orbit eccentricity and argument of perigee to freely drift during mission if the system is designed to accommodate the resulting variation in mission metrics such as range and range rate.

[View Full Paper]

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ANALYTICAL STATE PROPAGATION OF OBLATE SPHEROIDAL EQUINOCTIAL ORBITAL ELEMENTS FOR VINTI THEORY

Ashley D. Biria[*] and Ryan P. Russell[†]

Equinoctial orbital elements have been generalized from spherical geometry to the oblate spheroidal geometry of Vinti theory, a satellite theory that accounts exactly for oblateness and optionally J_3. For the symmetric potential, these nonsingular elements resolve the usual problems found in the classical elements associated with angle ambiguities. But their introduction is incomplete without developing an analytical solution in these nonsingular elements. In the present study, state propagation in time is investigated as a separate and self-contained endeavor, including derivations of the equinoctial constants of the motion and techniques to solve a generalized Kepler's equation. Multiple examples are presented. [View Full Paper]

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CELL-MAPPING ORBIT SEARCH FOR MISSION DESIGN AT OCEAN WORLDS USING PARALLEL COMPUTING

Dayung Koh,[*] Rodney L. Anderson[†] and Ivan Bermejo-Moreno[‡]

In this study, a cell-mapping approach is applied to various systems in the circular restricted three-body problem to obtain a rapid understanding of the global dynamics. The method is generic for various classes of problems including non-autonomous systems and different types of periodic solutions. The cell-mapping method also does not require previously known solutions as inputs, which is typical of continuation approaches, and no symmetric constraints are imposed. This method is especially applicable to a systematic periodic orbit search over a region of interest at one-period of integration. As additional strengths of the method, multiple-period solutions and bifurcation studies can be easily performed. In this study, the initial orbit search is applied to obtain an understanding of the orbit trade space at Europa and Enceladus. [View Full Paper]

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AAS 17-827

NONLINEAR DIFFERENTIAL EQUATION SOLVERS VIA ADAPTIVE PICARD-CHEBYSHEV ITERATION: APPLICATIONS IN ASTRODYNAMICS

John L. Junkins[*] and Robyn M. Woollands[†]

We present an adaptive approach for solving initial value problems using an accelerated Picard-Chebyshev method. The new algorithm retains the large convergence domain typical of Picard iteration, and importantly, accelerated terminal convergence typical of quasi-linearization. This approach is implemented for both first order and second order systems of differential equations. Including the error feedback terms leads to about a factor of two decrease in the number of iterations required for Picard convergence to near machine precision. We discuss the subtle but significant distinction between integral quasi-linearization for systems that are naturally first order, systems that are naturally second order (but re-arranged to be integrated in first order form), and systems that are naturally second order and integrated using a kinematically consistent modified Picard-Chebyshev iteration in *cascade form*. The adaptation technique introduced is self-tuning and adjusts the size of time interval segments and the number of nodes per segment automatically to achieve near-maximum efficiency. The technique also utilizes recent insights on local force models and adaptive force models that take advantage of the fixed point nature of Picard iteration. We demonstrate enhanced performance by solving benchmark problems in astrodynamics, specifically gravitationally perturbed near-Earth orbits. We compare the results with those obtained using an 8^{th} order Gauss-Jackson integrator, a 12^{th} order Runge-Kutta integrator and MATLAB's ODE45. The adaptive algorithm is more efficient than these competing methods, implemented as serial algorithms, while maintaining user prescribed accuracy tolerance ranging from engineering precision to near machine precision over at least seven weeks of orbit propagation. The method presented is well-suited for parallelization whereas the step-by-step methods are poorly suited to parallelization. [View Full Paper]

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SMALL BODY EXPLORATION

Session Chair:

Session 13: Jay McMahon

AAS 17-584

INVESTIGATION OF TRANSFERS TO STABLE SPACECRAFT ORBITS IN A CR3BP MODEL OF A BINARY ASTEROID SYSTEM

Kristen Tetreault,[*] Ann-Catherine Bokinsky,[†] Shane Ross[‡] and Jonathan Black[§]

A scenario of a spacecraft maneuvering to enter an orbit around the main body of a binary asteroid system is analyzed. In this simulation, a low thrust engine is used on a spacecraft entering this three-body system via a series of finite-time burns. An optimization problem is formulated to control the burn characteristics of the spacecraft as it attempts to enter a stable orbit about the primary body from a parking trajectory about the asteroid system. To ensure a realistic model, the Didymos 65803 binary asteroid from NASA's Asteroid Impact and Deflection Assessment mission will serve as the binary system. A transfer trajectory was achieved while optimizing for spacecraft stability with two burns executed. [View Full Paper]

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AAS 17-640

OPTIMIZATION PROCESS OF TARGET SELECTION FOR MULTIPLE ASTEROID ENCOUNTERS IN THE MAIN BELT

Alena Probst,[*] Oliver Ermertz[†] and Roger Förstner[‡]

The relevancy of the research on asteroids is mirrored in the growth and progress of connected, scientific fields over the last two centuries. The results obtained link the knowledge of their origin and development to the two big questions in science: *How did life develop?* and *How did the solar system evolve to its current appearance?* Hence, asteroid characterization missions are more important than ever. As the asteroid population is very diverse, a broad, close-up investigation of many different objects is recommended to define differences as well as similarities. The results serve as constraints and boundary conditions on the search for further insights. One efficient realization are missions that target several objects in a row, hopping from one to the next. With the amount of asteroids discovered, target selection becomes a challenge.

In this paper, two analyses are presented. First, the derivation of suitable pruning criteria for the database of asteroid bodies is presented. The analysis is based on a generic accessibility of virtual asteroids departing from a parking orbit in the main belt. As a second step, two target sequence optimization methods for multiple asteroid rendezvous missions are introduced and compared. The asteroid tour starts from and ends at the parking orbit used for the derivation of the pruning criteria. In order to enhance the flexibility and automation, the sequential target selection is based on solely the S/C departure state in position and time as well as the remaining fuel stock. [View Full Paper]

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AAS 17-662

SELECTED TRAJECTORY OPTIONS TO 2016 HO3

Brian D. Kaplinger[*] and Anthony Genova[†]

This paper presents the results of three different search strategies for trajectories to 2016 HO3 in the timeframe 2019-2028. Since many Lambert solvers result in impulses to this target exceeding 5.5 km/s due to the high solar inclination, a strategy utilizing the gravity of the Earth was proposed. The initial model used for sample trajectories is the circular, restricted, three-body problem (CR3BP) between the Sun and Earth-Moon barycenter. Trajectories were discovered near the stable manifolds for osculating periodic orbits to 2016 HO3, transit through L1/L2, and via Venus gravity assist after passage through L1. Selected examples are modeled in higher fidelity, and the Earth departure phase is analyzed. Some design considerations for such a mission are briefly considered. The trajectories proposed include impulses as low as 3.5 km/s for rendezvous, and 1.1 km/s for flyby, so far. Trajectory trades and further computation are ongoing. [View Full Paper]

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AAS 17-698

ROBUST OPTIMIZATION OF DESCENT TRAJECTORIES ON IRREGULAR-SHAPED BODIES IN THE PRESENCE OF UNCERTAINTY

Pablo Machuca,[*] Daniel González-Arribas,[†] David Morante-González,[†] Manuel Sanjurjo-Rivo[‡] and Manuel Soler[‡]

High levels of uncertainty are associated to the characterization of the environment around small bodies in the Solar System. In an effort to develop efficient methods to consider uncertainty in the analysis of missions to irregular-shaped bodies, the problem of robust and efficient optimization of descent trajectories in the presence of uncertainty is addressed in this paper. The gravitational field around the body is modeled using an optimized mascons approach, for computational efficiency and reduced approximation error. Random processes in the system are discretized and approximated using stochastic quadrature rules, which allow for efficient computation of relevant statistical quantities in the system. A single optimal control history is then solved for and applied to all discrete cases of the uncertain system. A general formulation for the problem of optimal descent on irregular-shaped bodies is developed, and the described methodology is applied to the problem of minimum impact velocity with uncertainty in the total mass of the body.

[View Full Paper]

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AAS 17-721

EVALUATION OF A RAPID TRANSFER DESIGN APPROACH FOR SMALL BODY APPLICATIONS[*]

Benjamin F. Villac[†] and Rodney L. Anderson[‡]

This paper discusses the challenges of applying a periodic orbit based rapid trajectory design method to small body orbiters. Using a sample mission scenario to asteroid EV5, a transfer design method based on pre-computed elementary transfers is applied to various orbital regimes that range from distant encounter to close-proximity operations. The computation of the elementary transfer dataset and the application of the associated combinatorial optimization highlight the key challenges of this problem, such as the down-selection of intermediary orbits and the application of constraints to obtain relevant transfers. [View Full Paper]

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AAS 17-731

ORBIT DESIGN FOR A PHOBOS-DEIMOS CYCLER MISSION

Bolys Sabitbek* **and Brian C. Gunter†**

Little is known about the Martian moons Phobos and Deimos, even though they have the potential to provide insight into the evolution of the Martian system, and could potentially serve as a staging site for a future Mars manned mission. While attempts to visit Phobos with dedicated missions have been attempted, to date none have been successful, and no dedicated mission to Deimos has been flown. As such, much of what is known about the structure and composition of either moon comes from a small collection of images. This study explores a class of stable cycler orbits that could visit both moons on a regular cadence, and can be tuned to fly-by one moon more frequently, or to vary the ground track coverage to obtain improved surface coverage. While the orbits described can be reached by a dedicated spacecraft with sufficient delta-V for a Mars insertion, the motivation here is that the spacecraft is already in an initial insertion orbit, such as a small-satellite rideshare on an existing Mars mission. Under this assumption, the results presented illustrate that the exploration of both Phobos and Deimos can be achieved with a spacecraft with capabilities of modern nanosatellites (cubesats). [View Full Paper]

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ON THE USE OF MEAN MOTION RESONANCES TO EXPLORE THE HAUMEA SYSTEM

Diogo M. Sanchez* and Antonio F. B. A. Prado†

In this work, Mean Motion Resonances (MMR) are used to create highly eccentric co-orbital orbits with Namaka, the inner moon of the dwarf planet Haumea. We found a region of instability nearby Namaka, caused by the quasi-super position of the critical semi-major axis of Haumea-Namaka (23,576.573 km) and Haumea-Hi'iaka (22,422.929 km). These orbits need to be retrograde, since prograde orbits cross the region of instability due to the variation of their semi-major axis. We used the method of the integral of the disturbing acceleration to analyze the region of instability. [View Full Paper]

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OUTER PLANET EXPLORATION

Session Chair:

Session 14: Paul Thompson

AAS 17-564

MANEUVER OPERATIONS DURING JUNO'S APPROACH, ORBIT INSERTION, AND EARLY ORBIT PHASE

Paul W. Stumpf,* Ram S. Bhat* and Thomas A. Pavlak*

The Juno spacecraft was launched on August 5, 2011 for a 1795-day journey to Jupiter, and arrived on July 5, 2016 with the successful Jupiter Orbit Insertion (JOI) maneuver. This paper will discuss the maneuver operations that took place starting from the Jupiter approach phase (specifically TCM11 on February 3, 2016) through JOI, and the first year of Juno orbital operations through OTM07. [View Full Paper]

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AAS 17-573

JUNO TRAJECTORY REDESIGN FOLLOWING PRM CANCELLATION*

Thomas A. Pavlak,† Jennie R. Johannesen† and John J. Bordi‡

In October 2016, the Juno spacecraft was operating in 53.5-day capture orbits and final preparations were underway for a Period Reduction Maneuver (PRM) to achieve the planned 14-day science orbits. However, one week before PRM execution, a main engine propulsion system anomaly prompted an indefinite PRM delay and immediate updates to the Juno reference trajectory. This paper outlines stop-gap trajectory design activities immediately following PRM delay and longer-term trajectory redesign considerations including various possible PRM epochs, orbit period, longitude grid characteristics, and eclipse avoidance strategies that culminated in the decision to cancel PRM and adopt a new 53-day reference trajectory. [View Full Paper]

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AAS 17-595

JUNO ORBIT DETERMINATION EXPERIENCE DURING FIRST YEAR AT JUPITER*

Shadan Ardalan,† John Bordi,‡ Nicholas Bradley,§ Davide Farnocchia,§ Yu Takahashi§ and Paul Thompson§

The Juno spacecraft successfully inserted into a polar orbit around Jupiter on 5-July-2016. Since the Jupiter Orbit Insertion (JOI) maneuver, Juno has completed six orbits around Jupiter. The mission plan at the time of JOI was for Juno to perform two 53.5-day capture orbits before executing a Period Reduction Maneuver (PRM) to place the spacecraft into its intended 14-day science orbit. This maneuver was canceled due to a concern with the propulsion system. As a result, the Juno spacecraft will remain in its longer orbit period for rest of its mission. This paper discusses the Navigation Team's experience: the orbit determination strategy and how it changed due to the cancellation of the PRM, challenges fitting the data during perijove, and how we reconstructed the trajectory during Juno's first year in orbit. [View Full Paper]

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AAS 17-596

CASSINI MANEUVER EXPERIENCE THROUGH THE FINAL TARGETED TITAN FLYBY AND THE GRAND FINALE

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Amassing valuable scientific information about the Saturnian system for 13 years, the Cassini spacecraft is now in the last phase of its mission. The Grand Finale, a series of 22 orbits with Cassini passing through a gap between Saturn's innermost ring and its upper atmosphere, began after the last targeted Titan flyby on April 22, 2017 and ends with the spacecraft plunging into Saturn on September 15, 2017. This paper reports on the maneuvers performed to achieve the final targeted Titan encounter and the maneuvers used to maintain the Grand Finale orbits. [View Full Paper]

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OPTICAL NAVIGATION DURING CASSINI'S SOLSTICE MISSION

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After nearly twenty years in flight, Cassini's mission at Saturn will conclude as it purposely dives into Saturn's atmosphere on September 15, 2017. Primarily to avoid moons potentially harboring conditions for life and with propellant very low, the intentional plunge into the atmosphere was set in motion years ago. We take this opportunity to give an overview of the optical navigation and its roles throughout the mission. The paper describes the navigation process and the evolution of optical navigation over the past thirteen years. The last equatorial phase of the Cassini mission was particularly challenging for the OD team as the Saturn system was not being estimated anymore, and it had been a few years since the last icy moon flybys. Science pictures of Enceladus one month prior to the Enceladus encounters confirmed the moon's position to be in good agreement with the Saturn system dynamical modeling used. This reduced Enceladus's absolute uncertainty by a factor of three, less than 1 km, and gave confidence the navigation team could achieve acceptable flybys and meet science objectives. [View Full Paper]

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AAS 17-633

INITIAL JUPITER ORBIT INSERTION AND PERIOD REDUCTION MANEUVER PLANS FOR JUNO

Jennie R. Johannesen,* Thomas A. Pavlak* and John J. Bordi†

This paper describes the initial plans for the New Frontiers Juno mission at Jupiter. It includes the considerable contingency planning for mission recovery if the Jupiter Orbit Insertion (JOI) burn to place Juno into a large capture orbit were interrupted or terminated on a burn timer setting, and the options for the mission if the Period Reduction Maneuver (PRM) burn to achieve the final orbit period were terminated early. The analyses were based on the assumption that 14-day orbits were the desired operational orbit period. [View Full Paper]

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AAS 17-714

JUICE: WHEN NAVIGATION DELTA-V COST IS REDUCED VIA TOUR REDESIGN

Arnaud Boutonnet,[*] Amedeo Rocchi[†] and Johannes Schoenmaekers[‡]

JUICE is the next ESA L-class mission towards Jupiter and its Galilean moons. After capture the spacecraft is injected into a series of Ganymede resonant transfers aiming at preparing the Europa science phase. The navigation of the Jupiter insertion is very costly due to many sources of uncertainties. The navigation DeltaV cost is usually reduced through optimal placement of stochastic manoeuvres or combined deterministic/stochastic manoeuvres. This paper presents an innovative approach allowing for a reduction of the DeltaV via the optimal selection among a set of modified tours. In other words deterministic and stochastic DeltaVs are optimised together. [View Full Paper]

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EARTH ORBITERS

Session Chair:

Session 15: Christopher Roscoe

The following paper was not available for publication:

AAS 17-783 Paper Withdrawn

AAS 17-563

THE SSL-100: ADCS FOR THE NEXT GENERATION OF LOW-COST, AGILE LEO SPACECRAFT

Erik A. Hogan,[*] Michael Homer[†] and Byoungsam (Andy) Woo[‡]

To support increasing demand in the 75-750 kilogram class of satellites, the SSL-100 bus was developed from the ground up. In contrast to the typical large geostationary satellites that SSL is known for, the SSL-100 is intended to serve as a platform for a variety of agile LEO mission profiles that require a high level of autonomy at a low cost point. In this paper, we highlight our approach to the design of the attitude determination and control system (ADCS) for the SSL-100 and discuss the challenges inherent in developing a highly-capable, reusable design using low-cost, off-the shelf components.

[View Full Paper]

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IMPULSIVE ORBIT CONTROL FOR MULTI-TARGET ACQUISITION

Sung-Hoon Mok,[*] Hyochoong Bang[†] and Henzeh Leeghim[‡]

This proceeding proposes an optimal impulsive solution to overfly designated ground targets. The analytical approximate solution of delta-v is derived, which consists of only longitude difference and the orbital revolution number. Then, the fuel-optimal solution can be simplified as a way of selecting the optimal revolution number only. The obtained single-target solution is extended to cases of two- and three- targets. Even in multi-target case, it is shown that the optimization parameters are only the revolution numbers, so the simplicity of the solution form remains. The general solution considering descending pass and J2 perturbation is also presented. Numerical examples demonstrate that the impulsive solution, in terms of firing instants and magnitudes, makes the satellite overfly desired targets in a timely manner. The proposed orbit-scheduling solution may be combined with the conventional attitude-scheduling problem, and as a result the integrated simultaneous scheduling may enhance the responsiveness of the earth observing mission further.

[View Full Paper]

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AAS 17-692

CONSTRAINED BURN OPTIMIZATION FOR THE INTERNATIONAL SPACE STATION

Aaron J. Brown* **and Brandon A. Jones†**

In long-term trajectory planning for the International Space Station (ISS), translational burns are currently targeted sequentially to meet the immediate trajectory constraints, rather than simultaneously to meet all constraints, do not employ gradient-based search techniques, and are not optimized for a minimum total delta-v (Δv) solution. Analytic formulations of the objective gradients and constraint gradients for the ISS trajectory are developed and used in an optimization solver to overcome these obstacles. Two trajectory examples are explored, highlighting the advantage of the proposed method over the current approach, as well as the potential Δv and propellant savings for the ISS in the event of propellant shortages. [View Full Paper]

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AAS 17-713

MODELING OF THERMAL HEATING AND THERMAL RADIATION PRESSURE DUE TO SUN AND ALBEDO WITH APPLICATION TO GRACE ORBIT AND ACCELEROMETER DATA

Florian Wöske,[*] Takahiro Kato,[†] Meike List[†] and Benny Rievers[†]

The precise modeling and knowledge of non-gravitational forces is of big interest to many scientific space missions. Thermal radiation pressure is often omitted even though it can be 5 to 25% of solar radiation pressure. We show a high precision modeling approach for all non-gravitational forces, considering heat fluxes origin from Sun, albedo and the satellite itself. We employ a finite element model of the GRACE gravity recovery mission with optical and thermal properties. GRACE accelerometer data are processed and the different modeled non-gravitational accelerations are compared and validated with GRACE accelerometer data. [View Full Paper]

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CLOUDSAT AT 11—NOW WHAT?[*]

Theodore H. Sweetser,[†] Mona M. Witkowski[‡] and Deborah G. Vane[§]

The CloudSat mission recently completed eleven years of on-orbit operations, providing unique radar profiles of the vertical structure of clouds. CloudSat is a member of the A-Train, an international constellation of Earth-science satellites at 705 km altitude with an ascending node at 1:30 PM local time. Five years into the mission, the CloudSat spacecraft survived a near-death experience when its battery developed a current-limiting impedance restriction. Dramatic changes were made to the operations of the spacecraft, allowing the mission to continue providing unique weather- and climate-related data on clouds. While several more years of operations are possible, a number of challenges still exist. We discuss the science, the history, and options for the future of CloudSat.

[View Full Paper]

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AAS 17-779

THE DESIGN OF THE REFERENCE ORBIT FOR NISAR, THE NASA-ISRO SYNTHETIC APERTURE RADAR MISSION[*]

Theodore H. Sweetser[†] and Sara J. Hatch[‡]

The NISAR mission plans to use a 12-day-repeating sun-synchronous orbit for repeat-pass interferometry at multiple time scales using SAR data. For the interferometry to work the radar measurements must be made from within a critical baseline, which happens if all of the orbits are maintained to be within a fixed tube around a reference orbit. This paper describes the choice of dynamical models used in defining such a reference orbit, the perturbative effects of dynamics not considered in the repeat orbit, and the process of designing the orbit to repeat. We also describe our method for sharing the repeat orbit among multiple mission participants who use different models and software.

[View Full Paper]

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AAS 17-796

HIGH ALTITUDE SUN-SYNCHRONOUS ORBITS AS SOLUTIONS OF THE CIRCULAR RESTRICTED SUN-EARTH-MOON-SATELLITE 4-BODY PROBLEM

Kazuaki Ikemoto* and Jun'ichiro Kawaguchi†

The altitudes of the well-known Sun-Synchronous Orbits (SSOs) are limited to a few thousand kilometers. This is because the synchronousness is realized by the J2-term of the geopotential. In this study, as solutions of the circular restricted 4-body (Sun, Earth, Moon and satellite) problem, new SSOs at altitudes on the order of magnitude of a million kilometers are reported. Lunar gravity assist plays an important role. Symmetries in the system are utilized to ease the numerical process. Besides the scientific interest, the result could be practical for reducing the variation of the heat input from the earth to satellites. [View Full Paper]

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AAS 17-818

MULTIOBJECTIVE TRAJECTORY OPTIMIZATION FOR ORBIT RAISING WITH COMBINED CHEMICAL-ELECTRIC PROPULSION

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

The typical strategy to place a satellite in the geostationary orbit (GEO) relies on chemical propulsion, which has proven to be effective and reliable. However, recent all-electric satellites attain propellant savings at the cost of a longer transfer time that results in a longer exposure to the Van Allen radiation Belts. A way to account for intermediate design solutions consists on allowing the two propulsion subsystems to coexist on the platform. Therefore, an optimization problem of interest consists on determining the transfer trajectory and the optimal propulsion system simultaneously. In this paper we formulate it as a Hybrid Optimal Control Problem with an unknown sequence of Electric and Coasting phases concurrently with an undetermined number of Chemical Firings. Our solution approach is based on a two step algorithm of increasing accuracy. In the first step, a heuristic algorithm together with a simplified control law for the electric engine, based on the Lyapunov feedback control method Q-law and relaxed constraints is to obtain a complete set of Quasi-Pareto-Optimal solutions in terms of propellant mass, time of flight and total radiation flux. Then, candidate solutions are deemed to be used in a second step as initial guesses for a direct collocation method, where the problem is transcribed into a nonlinear programming (NLP) problem by discretization, considering the full dynamics and the complete set of constraints. The proposed approach is applied to two hybrid transfer to GEO, one departing from GTO and another departing from LEO. Results show that hybrid platforms may represent a viable yet flexible option to widen the trade space for the next generation of GEO satellites. [View Full Paper]

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ORBIT DETERMINATION

Session Chair:

Session 16: Stefano Casotto

AAS 17-624

PRELIMINARY ANALYSIS OF GROUND-BASED ORBIT DETERMINATION ACCURACY FOR THE WIDE FIELD INFRARED SURVEY TELESCOPE (WFIRST)

Brad Sease,[*] Jessica Myers,[†] John Lorah[‡] and Cassandra Webster[§]

The Wide Field Infrared Survey Telescope is a 2.4-meter telescope planned for launch to Sun-Earth L_2 in 2026. This paper details a preliminary study of the achievable accuracy for WFIRST from ground-based orbit determination routines. The analysis here is divided into two segments. First, a linear covariance analysis of early mission and routine operations provides an estimate of the tracking schedule required to meet mission requirements. Second, a "simulated operations" scenario gives insight into the expected behavior of a daily Extended Kalman Filter orbit estimate over the first mission year given a variety of potential momentum unloading schemes. [View Full Paper]

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AAS 17-647

COMPARING DOUBLE DIFFERENCE GLOBAL NAVIGATION SATELLITE SYSTEMS AT MID LATITUDE

Krysta M. Lemm* and Gregory M. Carbott*

With the completion of the Russian Global Navigation Satellite System (GLONASS) it is important to evaluate the impact of GLONASS data on position accuracy for ground-based assets when post-processing techniques are employed. The GLONASS system can be used in isolation, or in combination with other Global Navigation Satellite Systems (GNSS) such as the United States Navstar Global Position System (GPS). GLONASS was designed to support navigation at higher latitudes, and previous research and testing for GLONASS performance at low- and mid-latitudes has been limited. This paper will focus on post-processed double-differenced data of a stationary mid-latitude land point over several collection time spans. Results show GLONASS improves positioning performance when used in concert with GPS, particularly when data is collected over a shorter time span. The performance improvement diminishes when longer data sets are collected and processed. [View Full Paper]

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AAS 17-668

RESEARCH AND DEMONSTRATION OF △DOR TRACKING BY SPARSE CALIBRATION

S. T. Han,[*] G. S. Tang,[†] J. S. Ping,[‡] Z. K. Zhang,[§] L. Chen,[‡] T. P. Ren,[‡] J. Sun,[‡] M. Wang[‡] and W. T. Lu[‡]

Differential One-Way Ranging(ΔDOR) based on short-alter-scan calibration is widely used for orbit measurement of a spacecraft. This paper presents the differential interferometric tracking with sparse calibration mode. Both deep space antennas keep pointing at the spacecraft while the target is in view of the stations. Interruption of telemetry and telecommand by traditional short-alter-scan mode could be avoided. During CE'3 100x15km encircle lunar orbit, interferometric tracking was conducted, by comparing ΔDOR observable with high accurate orbit, the residual delay error of the experiment tracking arc is about 1ns. [View Full Paper]

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BATCH SEQUENTIAL ESTIMATION WITH NON-UNIFORM MEASUREMENTS AND NON-STATIONARY NOISE[*]

Todd A. Ely[†] and Jill Seubert[‡]

Sequential estimation using the traditional discrete Kalman filter typically assumes the measurement time and state update time are coincident. This is often a poor assumption in realistic measurement scenarios where the data can be received from multiple sources at differing times. This paper develops the necessary algorithm adjustments needed for the Kalman filter to readily process measurement data that arrive at varying times and with non-stationary noise. The algorithm is applied to a relevant problem of orbit determination using one-way uplink radiometric tracking of a spacecraft (in the present case a Mars orbiter). [View Full Paper]

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AAS 17-755

GAUSSIAN MIXTURE KALMAN FILTER FOR ORBIT DETERMINATION USING ANGLES-ONLY DATA

Mark L. Psiaki*

A Gaussian mixture nonlinear Kalman filter is developed for satellite orbit determination using angles-only data. It is being developed for a space situational awareness system that must estimate orbits based on sparsely available optical tracking data. The Gaussian mixture framework is used to deal with nonlinear effects that cannot be handled by a conventional extended Kalman filter or an unscented Kalman filter. The Gaussian mixture filter consists of a bank of extended Kalman filters whose relative weights are affected by their relative abilities to fit the measurement data. It includes a re-sampling step between the dynamic propagation and the measurement update that enforces an upper bound on each mixand's covariance. This bound enables the algorithm to maintain a good approximation of the underlying Bayesian conditional probability density function despite nonlinearities. The filter's initial Gaussian mixture is derived from a short arc of angles-only measurement data and from constraints on the minimum periapsis and the maximum apoapsis. The filter has been tested using truth-model simulation data for several nearly geosynchronous cases. Reliable convergence and good accuracy can be achieved using once-per-night data arcs that are only 20 seconds long. [View Full Paper]

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AAS 17-793

INTERPOLATION ON THE UNIT SPHERE IN LAPLACE'S METHOD

Ethan Burnett[*] and Andrew J. Sinclair[†]

This paper proposes an alternative interpolation approach for the line-of-sight measurements in Laplace's method for angles-only initial orbit determination (IOD). The classical implementation of the method uses Lagrange polynomials to interpolate three or more unit line-of-sight (LOS) vectors from a ground-based or orbiting site to an orbiting target. However, such an approach does not guarantee unit magnitude of the interpolated line-of-sight path except at the three measurement points. The violation of this constraint leads to unphysical behavior in the derivatives of the interpolated line-of-sight history, which can lead to poor IOD performance. By adapting a spherical interpolation method used in the field of computer graphics, we can obtain an interpolated line-of-sight history that is always unit norm. The first and second time derivatives of this interpolation yield the estimated line-of-sight rate and acceleration used in Laplace's method. This new spherical interpolation method often leads to significant performance improvements in Laplace's IOD method, which will be demonstrated through careful study of simulation results.

[View Full Paper]

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AAS 17-794

OPTIMAL LINEAR ORBIT DETERMINATION

Andrew J. Sinclair[*] and T. Alan Lovell[*]

Modern methods for angles-only orbit determination traditionally write the line-of-sight measurement as a nonlinear function of the object's instantaneous position. An alternative is to consider taking a cross product of the measured line-of-sight vector with the instantaneous position. This leads to a rigorously linear measurement model, and suggests an alternative problem definition to minimize the residuals in these cross-product equations. This approach is analogous to the optimal linear attitude estimator. This paper analyzes the covariance of this optimal linear orbit determination, and considers the appropriate weighting scheme for the cross-product residuals. [View Full Paper]

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AN IMPROVED REPRESENTATION OF MEASUREMENT INFORMATION CONTENT VIA THE DISTRIBUTION OF THE KULLBACK-LEIBLER DIVERGENCE

Matthew J. Gualdoni[*] and Kyle J. DeMars[†]

Proper utilization of sensor networks is key in target-dense or measurement-scarce environments, such as in the creation and maintenance of reliable records for space objects in Earth orbit. In recent years, there have been many investigations of utilizing different information-theoretic measures as performance measures in allocating sensor tasks to maximize the information gained. More specifically, information divergences have been considered in sensor tasking schemes to effectively and efficiently utilize the available sensor resources. However, it is typical that only the expected information gain with respect to the measurement likelihood is considered, while the rest of the distribution of the divergence in question is disregarded. This work studies the full distribution of the Kullback-Leibler divergence and if the utilization of this knowledge when committing to an action regarding the acquisition of measurement information is beneficial. [View Full Paper]

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AAS 17-815

MINIMUM DIVERGENCE FILTERING USING A POLYNOMIAL CHAOS EXPANSION

Christine L. Schmid* and Kyle J. DeMars†

Bayesian filters for discrete-time systems make use of the Chapman-Kolmogorov equation and Bayes' rule to predict and update the uncertainty of a state. For nonlinear filtering problems, the Bayesian recursion is not guaranteed to close. An assumed density framework can be used to force the recursion to close, where one such realization is the minimum divergence filter, which seeks to minimize the Kullback-Leibler divergence of the assumed density with respect to the reference state density. This results in a moment matching problem, where the moments are traditionally approximated using Gauss-Hermite quadrature. An alternative solution is presented by replacing the Gauss-Hermite quadrature with a polynomial chaos expansion to reduce computational cost and provide a method that is more robust to distributional assumptions. The ability of the polynomial chaos expansion to compute the expected value of a random variable that cannot be assumed Gaussian is tested against a Gauss-Hermite quadrature approximation, unscented transform, and Monte Carlo sampling. Another test is preformed isolating the corrector of the minimum divergence filter with varied prior uncertainties. The two methods are then compared in an orbital state estimation problem. [View Full Paper]

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SMALL BODY MODELING

Session Chair:

Session 17: Roberto Furfaro

AAS 17-557

A COMPARISON OF GRAVITY MODELS USED FOR NAVIGATION NEAR SMALL BODIES

James K. Miller* and Gerald R. Hintz†

A number of gravity models are used for trajectory design, scientific investigations and navigation of spacecraft. Some gravity models are approximate and others are exact. Approximate models are adequate for trajectory design and some scientific investigations, but high precision models are required for navigation, particularly for orbit determination. The most demanding gravity model requirements are for orbit determination around large irregularly-shaped bodies. A harmonic expansion of Legendre polynomials and associated functions, while satisfactory for spherically-shaped planets, does not work well for large irregularly-shaped bodies such as comets or asteroids. Inside the sphere of maximum radius, the harmonic expansion diverges. Even outside the sphere of maximum radius, the harmonic expansion requires a high degree and order to obtain accurate orbit determination solutions.

In this paper, several gravity models are analyzed and compared to determine their suitability for navigation. Accuracy, number of parameters that need to be determined by the orbit determination filter and speed of computation that must include acceleration and variational partial derivatives are factors that must be considered. Another important factor is the ability to change the computation speed as a function of the required accuracy. For a harmonic expansion, this may be accomplished by changing the degree and order of the expansion. Changing the degree and order introduces an abrupt jerk to the trajectory, which probably would not affect trajectory design, but could seriously confuse the orbit determination filter. Gravity models that use point masses or mascons also have singularities that are a problem for orbit determination. Gravity models that involve numerical integration can be designed to make a seamless transition using error control.

[View Full Paper]

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AAS 17-619

AUTONOMOUS SHAPE ESTIMATION AND NAVIGATION ABOUT SMALL BODIES USING LIDAR OBSERVATIONS

Benjamin Bercovici,* Ann Dietrich† and Jay McMahon‡

This paper provides insight into the development of an autonomous attitude and shape registration framework used in conjunction with an autonomous relative navigation filter, both tailored for operations about small bodies such as asteroid Itokawa. These methods rely on Flash-Lidar data as their only measurement type. In particular, an instance of the Iterative-Closest-Point to Plane algorithm is used to simultaneously recover the target's attitude and blend it with the facet/vertex shape model being constructed in a feature-tracking-less fashion. Results demonstrate the capability of the joint framework to construct a shape model of the small body on-the-fly that is then utilized by the navigation filter during a closer orbit phase. Itokawa's volume was captured within 0:2% when observed from a 3-km orbit. A follow-up relative-navigation phase over a 1 km-radius terminator orbit allowed the spacecraft position to be determined within 5 meters while using the shape model previously reconstructed. Future work will improve the fidelity of the simulation and leverage the benefit from alternative shape parametrizations to increase the overall framework's performance and robustness. [View Full Paper]

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AAS 17-658

PARALLELIZED SMALL-BODY LANDER/HOPPER SIMULATIONS WITH DISTRIBUTED CONTACT AND PROCEDURAL NOISE

Stefaan Van wal,* Robert Reid† and Daniel Scheeres‡

A contact model for the interaction between a lander/hopper spacecraft and the surface of a targeted small body is derived. The surface is represented implicitly, allowing for fast distance computations to high-resolution shape models. The motion of the spacecraft is propagated relative to the rotating target body. A distributed normal force and torque is generated by spring-damper units attached to vertices that cover the spacecraft shell. A single friction force is applied at an effective application point and drives the sliding velocity of that point to zero. An expression for the sticking force that maintains zero sliding velocity is derived. Using a regularization technique, the transition between slip and stick is smoothed. Rolling resistance reduces the spacecraft angular velocity, while maintaining the slip state of the application point. The model is extensively tested on a flat plane, with particular attention given to the applied numerical tolerances. Sample simulations on a rotating sphere and the signed distance field of comet 67P/Churyumov-Gerasimenko illustrate relevant applications of the model. [View Full Paper]

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AAS 17-720

GEOMETRIC CONTROL FOR AUTONOMOUS LANDING ON ASTEROID ITOKAWA USING VISUAL LOCALIZATION

Shankar Kulumani, Kuya Takami and Taeyoung Lee*

This paper considers the coupled orbit and attitude dynamics of a dumbbell spacecraft around an asteroid. Geometric methods are used to derive the coupled equations of motion, which are defined on the configuration space of the special Euclidean group, and then a nonlinear controller is designed to enable trajectory tracking of desired landing trajectories. Rather than relying on sliding mode control or optimization based methods, the proposed approach avoids the increased control utilization and computational complexity inherent in other techniques. The nonlinear controller is used to track a desired landing trajectory to the asteroid surface. A monocular imaging sensor is used to provide position and attitude estimates using visual odometry to enable relative state estimates. We demonstrate this control scheme with a landing simulation about asteroid Itokawa.

[View Full Paper]

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AAS 17-743

MASCON MODELS FOR SMALL BODY GRAVITY FIELDS

Patrick T. Wittick* and Ryan P. Russell†

In the context of small bodies, mascon models can be attractive because they are simple to compute, implement, and parallelize. However, to achieve a reasonable surface accuracy, mascon models typically require too many elements to be competitive with other models. Here, mascon models are revisited, with the intent to minimize the number of elements, optimize the placement of the elements, and modify the base model of elements in order to improve computational efficiency, while enabling their use at low altitudes. The use of spherical harmonics elements, buried within a mascon model, is shown to offer model evaluation speedups and reduced memory footprints at little or no accuracy cost over homogeneous mascon models. The resulting mixed element models expand the design space for optimal packing structures while providing fast, accurate field evaluations to enable rapid small body trajectory searches. [View Full Paper]

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AAS 17-763

IMPROVED GRAVITY MODEL PERFORMANCE BY USING MIXED FIDELITY SHAPE MODELS FOR IRREGULARLY SHAPED SMALL BODIES

Jay W. McMahon*

This work investigates the use of mixed fidelity shape models to compute the gravitational acceleration around small bodies. These bodies have complicated gravity fields, especially near their surfaces, and the accelerations are generally computed using the polyhedral gravity model. In this work, an algorithm is developed for computing mixed resolution shapes with the goal of getting similar accuracy in the gravitational acceleration while reducing the computational load. Results show that this method can achieve accuracies in gravity computation similar to shapes with many more facets than the mixed resolution shapes here, but full integration into trajectory simulations is needed to determine if computational savings are significant. [View Full Paper]

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AAS 17-768

MODELING ASTEROIDS TO ASSIST IN ORBITING AND LANDING MISSIONS

Flaviane C. F. Venditti[*] and Evandro M. Rocco[†]

Asteroids are rotating bodies with asymmetric distribution of mass, which makes the gravitational field around them different from spherical bodies. In order to more accurately study the gravitational field around these objects, it is necessary to have a physical model. To simplify the model of an asteroid, it is common to use approximations to simple shapes such as ellipsoids. However, this may lead to an imprecise model, especially when the asteroid has a very asymmetric shape. Thus, a new methodology developed to model the gravitational field of the asteroids is presented, called Mascon-layer model.[‡] It consists in using a polyhedron shape model, which is built using observational data, thus giving a good approximation of the real shape of the object. This shape model is then transformed into layers of mass concentrations. The gravitational potential is obtained using the new model, and then applied to analyze very close orbits on the collision boundary, and very distant orbits on the verge of escaping the sphere of influence of the asteroid's gravitational field. Orbital maneuvers, using continuous low thrust in closed loop, were also performed. One of the advantages of the methodology developed is that it is possible to use a simpler approach, requiring less computational effort, but still using a reliable source for the shape model. [View Full Paper]

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AAS 17-781

PRACTICAL GALERKIN VARIATIONAL INTEGRATORS FOR ORBITAL DYNAMICS ABOUT ASTEROIDS

Dante A. Bolatti[*] and Anton H. J. de Ruiter[†]

This paper presents a practical approach to a class of symplectic integrators known as Galerkin variational integrators, that allow the construction of higher order integration methods. These integrators preserve energy in Hamiltonian conservative systems, and are highly accurate for long term integration. By properly configuring the control points and quadrature functions used to construct the integrator, practical equations of motion can be obtained for orbital trajectory propagation that are suitable for study of spacecraft dynamics about small bodies. Simulations obtained with these methods are compared to the traditional non-symplectic Runge-Kutta fourth-order method and a second-order variational integrator, focusing on the implications of energy conservation and accuracy of the method. [View Full Paper]

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AAS 17-823

STABILITY ANALYSIS OF COUPLED ORBIT-ATTITUDE DYNAMICS AROUND ASTEROIDS USING FINITE-TIME LYAPUNOV EXPONENTS

Shota Kikuchi,[*] Yuichi Tsuda[†] and Jun'ichiro Kawaguchi[‡]

This study investigates coupled orbit-attitude dynamics around asteroids subject to solar radiation pressure and gravity irregularities. The solutions of Sun-synchronous orbits with Sun-tracking attitude motion are analytically derived by applying linearization and averaging. To verify the validity of the analytical solutions, numerical simulations are performed based on non-linear coupled orbit-attitude equations of motion. In addition, the stability of such coupled motion is analyzed using finite-time Lyapunov exponents. It is demonstrated that the Sun-synchronous orbit-attitude coupled motions exhibit long-term stability under certain conditions, and thus, these motions are useful and feasible options for asteroid missions. [View Full Paper]

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AAS 17-825

FILTER ROBUSTNESS OF FLASH LIDAR BASED NAVIGATION AROUND SMALL BODIES

Ann Dietrich[*] and Jay W. McMahon[†]

This work explores the limits of using flash lidar measurements around an asteroid for orbit determination by testing the robustness of these methods to model errors. Previous work showed that flash lidar can provide accurate orbit determination with an onboard shape model, and is less computationally expensive than using the state-of-the-art optical navigation methods. Emulating pointing jitter as a random pointing offset error at each observation time is accurately resolved with the iterative least-squares filter. A low fidelity shape model is used in the onboard filters to increase computational efficiency, and the filters do not diverge. The majority of the state errors are captured with a sequential consider covariance analysis. The results of these studies add confidence to pursuing the use of flash lidar measurements for autonomous small body spacecraft navigation.

[View Full Paper]

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CONSTRAINED GLOBAL TRAJECTORY OPTIMIZATION

Session Chairs:

Session 18: Jacob Englander
Jonathan Aziz

AAS 17-598

WALKING THE FILAMENT OF FEASIBILITY: GLOBAL OPTIMIZATION OF HIGHLY-CONSTRAINED, MULTI-MODAL INTERPLANETARY TRAJECTORIES USING A NOVEL STOCHASTIC SEARCH TECHNIQUE

Arnold C. Englander[*] and Jacob A. Englander[†]

Interplanetary trajectory optimization problems are highly complex and are characterized by a large number of decision variables and equality and inequality constraints as well as many locally optimal solutions. Stochastic global search techniques, coupled with a large-scale nonlinear programming (NLP) solver, have been shown to solve such problems but are inadequately robust when the problem constraints become very complex. In this work, we present a novel search algorithm that takes advantage of the fact that equality constraints effectively collapse the solution space to lower dimensionality. This new approach "walks the filament" of feasibility to efficiently find the global optimal solution. [View Full Paper]

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AAS 17-605

GRAVITY-ASSIST TRAJECTORIES TO THE ICE GIANTS: AN AUTOMATED METHOD TO CATALOG MASS- OR TIME-OPTIMAL SOLUTIONS

Kyle M. Hughes,[*] Jeremy M. Knittel[*] and Jacob A. Englander[*]

This work presents an automated method of calculating mass (or time) optimal gravity-assist trajectories without a priori knowledge of the flyby-body combination. Since gravity assists are particularly crucial for reaching the outer Solar System, we use the Ice Giants, Uranus and Neptune, as example destinations for this work. Catalogs are also provided that list the most attractive trajectories found over launch dates ranging from 2024 to 2038. The tool developed to implement this method, called the Python EMTG Automated Trade Study Application (PEATSA), iteratively runs the Evolutionary Mission Trajectory Generator (EMTG), a NASA Goddard Space Flight Center in-house trajectory optimization tool. EMTG finds gravity-assist trajectories with impulsive maneuvers using a multiple-shooting structure along with stochastic methods (such as monotonic basin hopping) and may be run with or without an initial guess provided. PEATSA runs instances of EMTG in parallel over a grid of launch dates. After each set of runs completes, the best results within a neighborhood of launch dates are used to seed all other cases in that neighborhood—allowing the solutions across the range of launch dates to improve over each iteration. The results here are compared against trajectories found using a grid-search technique, and PEATSA is found to outperform the grid-search results for most launch years considered. [View Full Paper]

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AAS 17-654

GLOBAL, MULTI-OBJECTIVE TRAJECTORY OPTIMIZATION WITH PARAMETRIC SPREADING

Matthew A. Vavrina,[*] Jacob A. Englander,[†] Sean M. Phillips[‡] and Kyle M. Hughes[†]

Mission design problems are often characterized by multiple, competing trajectory optimization objectives. Recent multi-objective trajectory optimization formulations enable generation of globally-optimal, Pareto solutions via a multi-objective genetic algorithm. A byproduct of these formulations is that clustering in design space can occur in evolving the population towards the Pareto front. This clustering can be a drawback, however, if parametric evaluations of design variables are desired. This effort addresses clustering by incorporating operators that encourage a uniform spread over specified design variables while maintaining Pareto front representation. The algorithm is demonstrated on low- and high-thrust mission examples, and enhanced multidimensional visualization strategies are presented. [View Full Paper]

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AAS 17-701

FEASIBILITY OF LOW THRUST TRAJECTORY OPTIMIZATION APPLICATIONS TO DEBRIS REMOVAL MISSION DESIGN

Jason A. Reiter,[*] Andrew M. Goodyear,[*] Davide Conte[*] and Jason M. Everett[†]

The density of debris in Low Earth Orbit makes operating a spacecraft more difficult with the addition of every new satellite. Kessler proposed a scenario in which the density becomes high such that collisions between objects cascade and cause further collisions. Inspired by the 9th Global Trajectory Optimization Competition, a mission is theorized that employs low-thrust propulsion to optimally rendezvous with and deorbit debris to prevent such a scenario from ever occurring. A beam search clustering method was used to select a series of individual missions that maximize the number of debris pieces removed while minimizing the fuel cost. However, it was found that such a mission is likely to be infeasible due to the J2 perturbation effects and limitations of low-thrust optimization technology. [View Full Paper]

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AAS 17-715

STOCHASTIC EVENT-ROBUST DEOPTIMIZATION TECHNIQUE FOR LOW THRUST TRAJECTORY DESIGN

Yuichi Tsuda*

This paper describes a methodology to find almost-optimum trajectories which are robust against inflight stochastic events, such as navigation/guidance error and unexpected missed thrust due to temporal spacecraft malfunctions. A Monte-Carlo based solution search technique was developed which can generate robustness-increased trajectories by deoptimizing the original solution. Arbitrary practical control constraints can be imposed, and one can obtain a solution range in the neighborhood of the original solution which improves the stochastic events-robustness. The technique was applied to an asteroid sample-return mission Hayabusa2 to improve the missed-thrust recoverability, which are presented in detail in this paper. [View Full Paper]

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AAS 17-785

AUTOMATED SOLUTION OF LOW ENERGY TRAJECTORIES

Ryne Beeson,[*] Vishwa Shah,[†] Joshua Aurich[†] and Donald Ellison[*]

In this paper we introduce a framework for the automated solution of low energy trajectories. Specifically, we are interested in solving constrained global spacecraft trajectory optimization problems in multi-body regimes (e.g. cislunar missions) that leverage the natural global transport of the multi-body dynamical system to provide low propellant control solutions. A main difficulty in automated global solution of this type of problem has been automating dynamical systems techniques to find ideal candidate boundary conditions and then connecting these structures in a natural way for global and local optimization schemes to be successful. We demonstrate the evolving capability of our framework by solving a multi-phase low-thrust cislunar trajectory problem. [View Full Paper]

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AAS 17-788

APPLICATIONS OF THE MULTIPLE-SHOOTING DIFFERENTIAL DYNAMIC PROGRAMMING ALGORITHM WITH PATH AND TERMINAL CONSTRAINTS

Etienne Pellegrini* and Ryan P. Russell†

The first multiple-shooting transcription of a Differential Dynamic Programming algorithm was presented in the first part of this paper series. In the present paper, the Multiple-Shooting Differential Dynamic Algorithm is applied to a variety of constrained nonlinear optimal control problems, including sensitive spacecraft trajectory optimization problems. Both path and terminal constraints are treated using the Augmented Lagrangian approach of Powell, Hestenes, and Rockafellar for equalities and inequalities. The constraints treatment is developed and validated, and completes the algorithm of Part 1. The full algorithm is applied to constrained spacecraft trajectory optimization problems. The results for example applications demonstrate the advantages of the multiple-shooting approach's convergence properties over the single-shooting algorithm. [View Full Paper]

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FAST AND RELIABLE APPROXIMATIONS FOR INTERPLANETARY LOW-THRUST TRANSFERS*

Damon Landau†

A three-step process bridges the gap between low-fidelity solutions that ignore optimal dynamics and optimized solutions that are computationally expensive to generate. First, semi-analytic solutions for transfers with free time and angle characterize the evolution of the shape and orientation of the orbit. Next, optimal control theory supplies the thrust vector with variable specific impulse while satisfying flight time and transfer angle constraints. Transfers with the additional constraint of constant specific impulse then provide a more realistic thruster model for preliminary trade studies. These approximations deliver a hundredfold improvement in run time at the expense of a few percent error in mass.

[View Full Paper]

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AAS 17-833

SYNTHESIS OF HIGHLY INCLINED AND SHORT PERIOD SOLAR POLAR ORBIT WITH ELECTRIC PROPULSION

Takehiro Koyanagi[*] and Junichiro Kawaguchi[†]

Solar polar observation satellites should be in orbits highly inclined to the ecliptic plane. However, the delta-V required to achieve such orbit is too large to get with whichever propulsion system. From this situation, Ulysses, the only satellite on a high inclination orbit so far, used gravity-assist at Jupiter. Because Ulysses flew ballistically after Jupiter flyby, its orbit kept large and period was long. Therefore, solar polar observation time was short compared to orbit period and distance from the sun was about 2AU when observation. To solve these problem, a method called E-2-I conversion was invented. This method attains highly inclined and short period orbit ballistically by repeating Earth flyby after Jupiter flyby. Gravity-assist at Earth can make the orbit smaller, higher inclination and shorter period. Gravity assist at Earth affects weaker than that of Jupiter but by repetition of it can make semi-major axis of the orbit smaller than 1AU and inclination of it about 90 degrees. This is better for solar polar observation than that of Ulysses. However, there was still a problem. Because this method repeats Earth flyby, orbit period after each flyby must be rational number to meet Earth. Moreover, because of weakness of Earth gravity, Earth meeting period can become as long as 5 years and it takes 33 years to reach eventual orbit.

In this study, we shortened the whole mission period drastically with low thrust continuous propulsion represented by electric propulsion. In previous study, optimization analysis has been made to increase the orbital inclination angle itself using continuous thrust, but no attempt has been made to combine optimization trajectory by continuous thrust and E-2-I conversion. This study uses continuous thrust not for changing orbit plane which demand huge delta-V but for changing orbit period on the same orbit plane. For example, in ballistic case, the best orbit period after the 1.5 years' period orbit was 1.25 years not 1 year because Earth gravity is too weak to achieve 1 year period. Therefore, Earth meeting period became 5 years. However, even if it is impossible to change the orbit period from 1.5 years into 1 year by swing-by. [View Full Paper]

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AAS 17-837

SPACE TRAJECTORY OPTIMIZATION USING EMBEDDED BOUNDARY VALUE PROBLEMS

David Ottesen[*] and Ryan P. Russell[†]

The proposed algorithm for preliminary spacecraft trajectory design is a gradient-based, direct method that minimizes a sum of impulsive maneuvers, generalized for spacecraft dynamics, but can benefit from fast and robust two-body approximations. The solution to many short and ballistic embedded boundary value problems on the inner-loop enforces position continuity for every optimization iteration, reducing the burden on any outer-loop optimizer. The many impulsive maneuvers between solutions lead to a natural approximation for low-thrust trajectories. Cost and constraint boundary value problem partial derivatives are derived and examples are provided. The algorithm draws from legacy works including the Lambert problem and primer vector theory. [View Full Paper]

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CONSTELLATIONS AND FORMATIONS

Session Chair:

Session 19: Matthew Wilkins

The following paper was not available for publication:

AAS 17-661 Paper Withdrawn

DEPLOYMENT AND CONTROL ALGORITHMS FOR WHEEL CLUSTER FORMATION SATELLITES[@]

Chia-Chun Chao[*] and Victor S. Lin[†]

A simple and elegant algorithm to populate a cluster around a center satellite was derived based on the concept of wheel formation in the same orbit plane. The algorithm of using small eccentricity vector separation to place those satellites on single or multiple wheel-shaped sub-orbits of at least 10 companion satellites gives desirable relative motion to the center satellite with safe separation distance among all the companion satellites. Numerical integration results show that with properly synchronized initial semi-major axis of each companion spacecraft with identical design, the desired wheel formation can last for months without stationkeeping at GPS and GEO altitudes. A set of optimized control strategies were developed and simulated for keeping the satellites in close formation. Without out-of-plane deviations and control, the cost of fuel consumption is minimized. This generalized wheel cluster formation can be applied to all types of orbits, such as LEO, MEO, GEO and HEO (Molniya, GTO and Tundra), as well as for artificial satellites orbiting other planets. [View Full Paper]

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AAS 17-601

LONG-TERM STABILITY OF COMMON-INCLINATION SATELLITE CLUSTERS*

Stuart J. Gegenheimer†

A cluster of satellites is a group of satellites in carefully specified close orbits, such that the satellites passively remain within a specified bounded area. In this paper, we examine several strategies for initial setup to minimize cluster deformation due to orbital perturbations. We then use these strategies in an assessment of the stability of three common-inclination cluster types in four orbital regimes using a high fidelity orbit propagator. Results show that it is possible to set up clusters which are passively stable over 90 days in LEO, one to two years in MEO, and five years in GEO. Stability of clusters is highly sensitive to the initial orbital elements of the cluster members and the area-to-mass ratios of those satellites. The stable clusters shown in this paper suggest very low propulsion costs for formation keeping of these clusters. [View Full Paper]

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AAS 17-607

SATELLITE CONSTELLATION ORBIT DESIGN TO ENABLE A SPACE-BASED RADIO INTERFEROMETER

Sonia Hernandez,[*] Jeffrey R. Stuart,[*] David M. Garza,[*] Stephen B. Broschart,[*] Sebastian J. I. Herzig[*] and Steve A. Chien[*]

Two different design methods for a networked constellation of N small satellites are presented. In the first method, the (linear) Clohessy-Wilthsire equations are used as an initial design tool, followed by conversion to a two-body model. Discrepancies between the linear and nonlinear solutions are minimized in the conversion process. The second method utilizes invariant manifold theory, by perturbing a reference trajectory in different directions along the center eigenvectors. Both methods require $5N$ parameters to fully define a constellation. In a relative, rotating frame of the reference path, the spacecraft appear as periodic ellipses of varying sizes. Deployment, reconfiguration using propulsive maneuvers, and station keeping costs for an example mission scenario are addressed.

[View Full Paper]

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AAS 17-760

RESULTS OF THE APOGEE-RAISING CAMPAIGN OF THE MAGNETOSPHERIC MULTISCALE MISSION

Trevor Williams,[*] Neil Ottenstein,[†] Eric Palmer[†] and Jacob Hollister[†]

This paper describes the apogee-raising campaign of the Magnetospheric Multiscale mission, where the spacecraft increased their apogee radii from 12 to 25 Earth radii in a total of 98 maneuvers. These maneuvers included an initial formation resize set to spread the spacecraft apart for safety, 32 apogee-raise delta-v maneuvers, their associated slews, four perigee-raise maneuvers and the associated slews, and finally a set of maneuvers to get back into formation. These activities were all accomplished successfully and on schedule with no anomalies, and at a fuel consumption somewhat less than predicted. As a result, MMS was set up ready to carry out *in situ* studies of magnetic reconnection in the magnetotail, with sufficient fuel remaining for a significant extended mission.

[View Full Paper]

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AUTONOMOUS OPERATIONS OF LARGE-SCALE SATELLITE CONSTELLATIONS AND GROUND STATION NETWORKS

Giovanni Minelli,[*] Mark Karpenko,[†] I. Michael Ross[‡] and James Newman[§]

A dynamic optimization problem is employed to aid operators of large-scale satellite constellations with automated mission planning and data collection. Traditional techniques focus on graph-theoretic ideas that use heuristics to simplify the problem. The solution presented in this paper is formulated as a dynamic optimization problem that scales linearly as the number of satellites and ground stations increases. The problem formulation is implemented with the DIDO© pseudospectral optimal control solver to produce deconflicted ground antenna slew trajectories as a function of parameters and constraints used commonly by satellite operators. In this paper, one such factor, space-to-ground link margin, is used for the proof of concept. Other parameters can include mission priority, asset availability, and onboard spacecraft health. The specific problem solved here is to optimally slew ground-based antennas between multiple satellites that are simultaneously in view of one or more earth stations. The approach is tested using orbiting CubeSats and the Mobile CubeSat Command and Control (MC3) network. [View Full Paper]

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HETEROGENEOUS CONSTELLATION DESIGN METHODOLOGY APPLIED TO A MARS-ORBITING COMMUNICATIONS AND POSITIONING CONSTELLATION

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

This research develops software that applies model-based systems engineering design optimization to the problem of satellite constellation design. The software uses a genetic algorithm solver to generate and evaluate candidate solutions to a set of user-defined missions given allowable ranges of satellite and orbital parameters. The methodology allows for the comparison of single-satellite constellations and disaggregated heterogeneous constellations. As a sample case, the problem of designing a Mars-orbiting position, navigation, timing, voice communications, and data relay constellation is examined. The optimization determined that a highly inclined Walker Delta constellation of forty-five multifunction satellites was the best solution. [View Full Paper]

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LOW-ENERGY MISSION DESIGN

Session Chair:

Session 20: Diane Davis

AAS 17-587

DISPOSAL INVESTIGATIONS FOR ESA'S SUN-EARTH LIBRATION POINT ORBITERS

Florian Renk[*] and Stijn Lemmens[†]

The European Space Agency has been and is currently operating spacecraft about the Sun-Earth Libration Points 1 and 2. More orbiters are planned to be sent to these locations in the future as well. Since the Sun-Earth Libration point orbits are unstable a dedicated strategy is required to minimize the risk of the spacecraft returning towards the Earth and penetrating the LEO and GEO protected regions or even re-entering the Earth's atmosphere in an uncontrolled fashion. For the heliocentric disposal a one- or two-manoeuvre strategy can be chosen with different drift times between the two manoeuvres. In addition to the different manoeuvre strategy the size of the libration point orbit is also an important contributor to the Earth-Moon system return probability. Thus as one example typical large amplitude halo orbits are studied, which can be reached via the so called free transfer trajectory. Spacecrafts going in these types of orbits are usually observatories like Herschel, Euclid, JWST, Ariel or Plato. However, some of the spacecrafts like Planck or Gaia require small amplitude Lissajous orbits for their survey missions; this is the second class of orbits studied. The general results for the trade between manoeuvre sizes and drift duration (if applicable) will be presented and in addition the detailed LISA Pathfinder disposal investigations will be presented. Based on the results of this study LISA Pathfinder conducted the final disposal manoeuvre centered around the 9th of April 2017. This leads to practical experience on dealing with space debris mitigation requirements for Sun-Earth Libration Points, and input for international standardisation on this topic. Another aspect concerns the upper stages used for the launch of libration point S/C and their long term behaviour. The considerations with respect to space debris mitigation requirements will also be discussed. [View Full Paper]

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AAS 17-593

DYNAMICS AND STABILITY OF SUN-DRIVEN TRANSFERS FROM LEO TO GEO

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

This paper discusses the design of transfers from low-Earth to geostationary orbits. Traditionally, the inclination change and periapse raising on the transfer trajectories are performed using a combination of in-plane and out-of-plane maneuvers. For this research, all inclination change and periapse raising is performed through the use of solar gravity. For high initial inclinations, the required ΔV can be significantly lowered, as compared to the more classic geostationary transfer trajectories. A characterization of the transfers' response to missed and imperfect maneuvers is performed to identify the robustness of the transfers. [View Full Paper]

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AAS 17-597

DYNAMICAL STRUCTURES IN A COMBINED LOW-THRUST MULTI-BODY ENVIRONMENT

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

Low-thrust trajectory design is challenging as the spacecraft position, velocity, and control histories must be specified simultaneously. Traditional approaches typically generate a single trajectory and control law via optimization algorithms. However, such solutions generally depend strongly on a feasible design that is input to the optimization process. Rather than seeking an optimal control law for each specific design problem, the focus of this investigation is additional insight from the exploration of a combined low-thrust multi-body dynamics model to guide the preliminary design process. Characteristics of key dynamical structures such as equilibrium points, periodic solutions, and manifold arcs are identified and compared to the well-understood circular restricted 3-body problem dynamics. [View Full Paper]

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AAS 17-653

TRAJECTORY DESIGN AND STATION-KEEPING ANALYSIS FOR THE WIDE FIELD INFRARED SURVEY TELESCOPE MISSION

Natasha Bosanac,[*] Cassandra M. Webster,[†]
Kathleen C. Howell[‡] and David C. Folta[§]

The Wide Field Infrared Survey Telescope (WFIRST) is an upcoming NASA-led observatory that will complete wide-field imaging and near-infrared sky surveys from a spacecraft in the Sun-Earth L_2 region. To identify a feasible mission trajectory, subject to geometric and maneuver constraints, an interactive trajectory design procedure, supported by dynamical systems techniques, is developed. This rapid and well-informed approach is implemented as a module of Purdue University's Adaptive Trajectory Design tool. In this paper, a feasible mission trajectory is constructed and output to a higher-fidelity modeling environment. Furthermore, station-keeping maneuvers are computed using a mode analysis strategy. [View Full Paper]

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AAS 17-687

FROM GTO TO BALLISTIC LUNAR CAPTUREUSING AN INTERIOR LAGRANGE POINT TRANSFER

Anthony L. Genova*† and Brian Kaplinger‡

The presented trajectory design connects a geosynchronous transfer orbit to lunar orbit via ballistic lunar capture. This design utilizes two lunar flybys to raise perigee to lunar distance and enter a high-Earth orbit (HEO) to set up an interior transfer through the Earth-Moon Lagrange points L1 and L2. This design is compatible with spacecraft equipped with propulsion systems that lack sufficient thrust to enter lunar orbit from a traditional lunar orbit transfer. Additionally, the utilized HEO can act as a cislunar staging orbit with the ability to send supplies from Earth to a manned space station in lunar orbit. [View Full Paper]

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AAS 17-695

PATCHED PERIODIC ORBITS: A SYSTEMATIC STRATEGY FOR LOW ENERGY TRANSFER DESIGN

Ricardo L. Restrepo[*] and Ryan P. Russell[†]

The design of low energy transfers is in general a tedious, time consuming task due to the high dynamical complexity of multi-body environments. A new systematic strategy, which seeks to ease the complexity of this task, is presented. In this model, we show how precomputed three-body periodic orbits can be patched together to give rise to complex trajectories. The patched periodic orbits in the restricted three body problem is analogous to the patched conics of the two body problem. The work focuses on the design of capture and escape trajectories, as well as transfers around the minor body of the three-body system. Several examples are presented, with emphasis on the Jupiter-Europa and Earth-Moon systems. [View Full Paper]

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COMPUTING LIBRATION POINT HYPERBOLIC INVARIANT SETS USING ISOLATING BLOCKS*

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

Earlier work focused on the computation of isolating blocks around the libration points in the circular restricted three-body problem and the use of these isolating blocks to compute the stable and unstable manifolds of the hyperbolic invariant set around the libration points. In this study, the hyperbolic invariant set, or the invariant three-sphere of solutions, is studied using the asymptotic approaches of the stable manifold to the periodic and quasiperiodic orbits contained within the invariant three-sphere. A new bisection method is used to compute trajectories that follow the invariant three-sphere and study these trajectories in more detail. [View Full Paper]

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AAS 17-711

SOLAR SAILING AT THE L4/L5 LIBRATION POINTS

Ariadna Farrés[*] and Narcís Miguel[†]

In this paper we focus on the dynamics of a solar sail in the vicinity of the Lagrangian points L4/L5. These points are linearly stable and so are the families of quasi-periodic orbits around them. Moreover, there is a region of effective stability around them, where the trajectory of a satellite will remain there for more than 1000 years. We will describe these regions and see how they are affected by the solar radiation pressure. A good understanding of these regions and of how to reach them would enable a novel space weather mission. [View Full Paper]

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AAS 17-746

TRAJECTORY OPTIMIZATION TO THE HALO ORBIT IN FULL FORCE MODEL USING EVOLUTIONARY TECHNIQUE

Gaurav Vaibhav,* B. S. Kiran,† Kuldeep Negi,‡
Atiksha Sharma§ and Saransh Shrivastava**

Aditya-L1 is the first conceived solar mission of Indian Space Research Organization (ISRO) in which the spacecraft will be placed in a non-planar periodic orbit (called halo orbit) around Sun-Earth L1 (SE-L1) libration point. This paper focuses on the mission design to the Sun-Earth L1 halo orbit considering the mission and launcher constraints. The mission design problem to the halo orbit broadly involves two major steps- Halo orbit design and selection and design of optimized transfer trajectory design to achieve the same, starting from Earth elliptic parking orbit (EPO). In this paper, the Halo orbit generation and transfer trajectory design have been initiated in CRTBP with backward propagation and its results have been fed to the developed full force model for the final design. Halo orbit selection is done considering mission and scientific requirements. Differential Evolution optimization algorithm has been developed as independent software to generate exact initial conditions for the halo orbit. Optimization of backward transfer trajectory design has also been carried out with the Differential Evolution. Transfer trajectory injection (TTI) ΔV, right ascension of ascending node (RAAN) and argument of perigee (AOP) obtained from the backward design were given as inputs to the forward trajectory design with full force model for propagation. The forward transfer trajectory was refined with full force model to achieve the desired Halo orbit insertion. [View Full Paper]

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AAS 17-759

EFFICIENT NRHO TO DRO TRANSFERS IN CISLUNAR SPACE[*]

Gregory Lantoine[†]

There has been recently a growing interest in cislunar missions, in particular for supporting human deep space exploration. Understanding the dynamical environment between various cislunar orbits is therefore useful. The current study is focused on finding efficient transfer trajectory options between a Near-Rectilinear Halo Orbit (NRHO) and a Distant Retrograde Orbit (DRO) in the Earth-Moon system. A general methodology is introduced to design these transfers in a systematic way, including the use of solar perturbations and lunar flybys. Representative solutions are presented and compared in terms of delta-v and flight time, including a transfer requiring 56 m/s only. [View Full Paper]

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AAS 17-784

RAPID APPROXIMATION OF INVARIANT MANIFOLDS USING MACHINE LEARNING METHODS

Vishwa Shah* and Ryne Beeson†

Low-energy mission design in the three-body model leverages invariant manifolds to obtain low-propellant solutions. Optimizing these trajectories requires generating manifolds and searching for the optimal manifold insertion point. Typically, manifolds are generated using numerical methods which can take up to several seconds, thus making the generation of these structures in an optimization framework computationally intractable. In this paper we will explore the application of machine learning algorithms to enable rapid approximation of these structures. The regression models will then be used within an optimization framework. The robustness, accuracy and computational advantages will be benchmarked against Cubic Convolution based approximation methods.

[View Full Paper]

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RELATIVE MOTION

Session Chair:

Session 21: Renato Zanetti

The following papers were not available for publication:

AAS 17-736 Paper Withdrawn

AAS 17-738 Paper Withdrawn

AAS 17-641

RELATIVE MOTION EQUATIONS IN THE LOCAL-VERTICAL LOCAL-HORIZON FRAME FOR RENDEZVOUS IN LUNAR ORBITS

Giovanni Franzini[*] and Mario Innocenti[†]

In this paper, a set of equations for relative motion description in lunar orbits is presented. The local-vertical local-horizon frame is selected to describe the relative dynamics of a chaser approaching a target in lunar orbit, allowing the development of relative guidance and navigation systems for rendezvous and docking. The model considers the Earth and Moon gravitational influence on the two spacecraft, which are assumed to have negligible masses. The proposed equations are intended for the study of rendezvous missions with a future cis-lunar space station, whose development is currently investigated by several space agencies as the next step for space exploration. [View Full Paper]

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AAS 17-688

ORBITAL ELEMENT-BASED RELATIVE MOTION GUIDANCE ON J_2-PERTURBED ECCENTRIC ORBITS

Bradley Kuiack[*] and Steve Ulrich[†]

One of the challenges of autonomous guidance and control of formation flying is related to the on-board prediction of the relative motion between both spacecraft, which has to remain accurate over long propagation periods and be valid for large separation distances on highly elliptical orbits. In this context, this paper addresses the problem of nonlinear analytical guidance for spacecraft formation flying reconfiguration maneuvers. Specifically, a nonlinear analytical solution for predicting the radial, along-track, and cross-track relative motion on J_2-perturbed elliptical orbits is first obtained and then used in a back-propagation scheme for closed-loop guidance purposes. Finally, the relative orbital element-based guidance solution is combined with an impulsive controller to demonstrate its efficiency in terms of propellant savings to execute a reconfiguration maneuver over a period of ten orbits. [View Full Paper]

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DISTRIBUTED SPACECRAFT PATH PLANNING AND COLLISION AVOIDANCE VIA RECIPROCAL VELOCITY OBSTACLE APPROACH

Sittiporn Channumsin,* Gianmarco Radice† and Matteo Ceriotti‡

This paper presents the development of a combined linear quadratic regulation and reciprocal velocity obstacle (LQR/RVO) control algorithm for multiple satellites during close proximity operations. The linear quadratic regulator (LQR) control effort drives the spacecraft towards their target position while the reciprocal velocity obstacle (RVO) provides collision avoidance capabilities. Each spacecraft maneuvers independently, without explicit communication or knowledge in term of collision avoidance decision making of the other spacecraft in the formation. To assess the performance of this novel controller different test cases are implemented. Numerical results show that this method guarantees safe and collision-free maneuvers for all the satellites in the formation and the control performance is presented in term of Δv and fuel consumption. [View Full Paper]

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AAS 17-739

WAYPOINT-OPTIMIZED CLOSED-LOOP GUIDANCE FOR SPACECRAFT RENDEZVOUS IN RELATIVE MOTION

Roberto Furfaro,* Roberto Ruggiero,† Francesco Topputo,‡ Marco Lovera§ and Richard Linares**

The design of a closed-loop guidance algorithm for autonomous relative motion is an important issue within the field of orbital dynamics. In this paper, we develop a closed-loop, waypoint-based, quasi-optimal algorithm that can be employed to execute autonomous rendezvous in relative motion. Specifically, the deputy spacecraft is executing an autonomous rendezvous with the chief spacecraft via a modified version of the zero-effort-miss/zero-effort-velocity (ZEM / ZEV) feed-back guidance. Here, the concept of waypoints-based guidance is introduced; they are defined as intermediate position and velocity targets between the departure point and the real final rendezvous. The position and velocity guidance is therefore divided in intervals. The ZEM/ZEV guidance parameters, represented by the coordinates of the final desired position, the components of the final required velocity and the time needed to reach these targets, will be different depending on the time interval. To determine the guidance parameters, referred to as waypoints parameters, different strategies are analyzed. Specifically, a series of optimization problems, based on the minimization of the fuel consumption constrained by the need to achieve high level of position and velocity accuracy, are formulated and solved. The first the case analyzed is the one in which the position trajectory of the spacecraft is unconstrained. The dynamical models considered for this case are the Clohessy-Wiltshire-Hills (CWH) model (circular orbit) and the Linearized equations of relative motion (LERM) model (elliptic orbit). Then, a more challenging case is studied: some nonlinear constraints related to the entire position trajectory are introduced in the optimization problem formulation. It is demonstrated that in all scenarios, the performances are satisfactory both from the point of view of the mass propellant expenditure and of the final position and velocity errors. Finally, the robustness of the waypoint-based ZEM/ZEM guidance is tested by simulating the closed-loop guidance in a higher fidelity dynamical model comprising the Restricted-two-body-problem (R2BP) nonlinear model with perturbations, expressed in form of acceleration. In addition to disturbances, a Monte Carlo analysis is conducted to test the system under off-nominal conditions. The results show that the waypoint-based ZEM/ZEV feedback guidance is able to execute not only precise but also quasi-optimal rendezvous maneuvers in perturbed working conditions. [View Full Paper]

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A NEW TIME-EXPLICIT J2-PERTURBED NONLINEAR RELATIVE ORBIT MODEL WITH PERTURBATION SOLUTIONS

Eric A. Butcher,[*] Ethan Burnett,[†] Jingwei Wang[†] and T. Alan Lovell[‡]

A new J2-perturbed time-explicit relative orbit model is developed including the effects of nonlinearities up to third order, chief orbit eccentricity, and J2 perturbation of both the chief and deputy orbits. The J2 acceleration is not averaged and the kinematics for perturbed relative motion are treated correctly. Numerical simulations for the case of vanishing chief eccentricity illustrate the lower error of the proposed model compared with that of the HCW solution. Finally, a perturbation technique is used to obtain analytical J2-dependent corrections to the HCW solution and to previously obtained analytical perturbation solutions that account for nonlinearity effects and chief orbit eccentricity, which are special cases of the J2-dependent analytical solution obtained here. [View Full Paper]

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AAS 17-791

APPROXIMATE CLOSED FORM SOLUTIONS OF SPACECRAFT RELATIVE MOTION VIA ABEL AND RICCATI EQUATIONS

Ayansola D. Ogundele,[*] Andrew J. Sinclair[†] and S. C. Sinha[‡]

Visualizing the relative motion using the Keplerian orbital elements simplifies the orbit description better than the use of Hill frame coordinates. Rather than using position and velocity the use of orbital elements has benefit of having only one term (anomaly) that changes with time out of the six orbital elements and this reduced the number of terms to be tracked from six to one. In this paper, with appropriate transformations, the evolution nonlinear equation of motion, which describes the dynamics of the relative motion of deputy spacecraft with respect to the chief spacecraft in terms of the orbit element differences, is transformed into third-order polynomial Abel-type nonlinear spacecraft relative equations of motion from which we obtained Riccati-type (second-order) equations. Using particular solutions of the equations general closed analytical form of the solutions are developed. [View Full Paper]

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SPACECRAFT GUIDANCE, NAVIGATION AND CONTROL

Session Chairs:

Session 22: Sean Wagner

Session 24: Christopher D'Souza

The following paper was not available for publication:

AAS 17-555 Paper Withdrawn

ORBIT DETERMINATION COVARIANCE ANALYSES FOR THE PARKER SOLAR PROBE MISSION

Drew Ryan Jones,* Paul Thompson,† Powtawche Valerino,* Eunice Lau,* Troy Goodson,* Min-Kun Chung* and Neil Mottinger*

This paper details pre-launch navigation covariance analyses for the Parker Solar Probe mission. Baseline models and error assumptions are outlined. The results demonstrate how navigation will satisfy requirements and are used to define operational plans. A few sensitivities are identified and the accompanying investigations are described. Predicted state uncertainty results show that most requirements are met with substantial margin. Moreover, navigation sensitivities may be accommodated operationally and this has been incorporated into project planning. Detailed results are presented only for select launch dates, however twenty unique trajectories (one per launch opportunity) have been assessed. [View Full Paper]

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AAS 17-580

MAGNETOSPHERIC MULTISCALE MISSION NAVIGATION PERFORMANCE DURING APOGEE-RAISING AND BEYOND

Mitra Farahmand,* Anne Long,† Jacob Hollister,‡
Julie Rose‡ and Dominic Godine‡

The primary objective of the Magnetospheric Multiscale (MMS) Mission is to study the magnetic reconnection phenomena in the Earth's magnetosphere. The MMS mission consists of four identical spinning spacecraft with the science objectives requiring a tetrahedral formation in highly elliptical orbits. The MMS spacecraft are equipped with onboard orbit and time determination software, provided by a weak-signal Global Positioning System (GPS) Navigator receiver hosting the Goddard Enhanced Onboard Navigation System (GEONS). This paper presents the results of MMS navigation performance analysis during the Phase 2a apogee-raising campaign and Phase 2b science segment of the mission. [View Full Paper]

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ENHANCED Q-LAW LYAPUNOV CONTROL FOR LOW-THRUST TRANSFER AND RENDEZVOUS DESIGN[*]

Demyan V. Lantukh,[†] Christopher L. Ranieri,[‡]
Marc D. DiPrinzio[§] and Peter J. Edelman[†]

Improvements to proximity quotient (Q-law) Lyapunov feedback for generating low-thrust transfers are demonstrated in terms of both numerical properties and the ability to do full six-state targeting. Numerical improvements include the use of a deadband for chatter reduction and an L-infinity norm based effectivity parameter. Fast variable targeting is accomplished by augmenting the semimajor axis target with a scaled bias to promote simultaneous convergence of the semi-major axis and true longitude.

[View Full Paper]

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AAS 17-599

OPTICAL-BASED KINEMATIC POSITIONING FOR DEEP-SPACE NAVIGATION*

Stephen B. Broschart,† Nicholas Bradley† and Shyam Bhaskaran‡

NASA's Deep Space 1 mission demonstrated that a spacecraft can be navigated autonomously during deep-space cruise operations using only images of distant asteroids as measurements. This paper derives an approximation of the position estimate accuracy that can be achieved with this technique based on the assumption of multiple, simultaneous line-of-sight measurements. This achievable accuracy is computed for locations across the solar system, which can be used to estimate cruise navigation performance as a function of spacecraft trajectory. It is shown that an on-board optical navigation system can achieve kinematic position estimate accuracies of better than 100 km throughout the inner solar system with a high-performance camera and from many hundred to several thousand kilometers with a low-end camera. Beyond the main-asteroid belt, the feasibility of this approach suffers due to lack of targets. A case-study implementation of this approach for the upcoming InSight mission to Mars is also presented. [View Full Paper]

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AAS 17-660

ASSESSING ORBIT DETERMINATION FOR A LUNAR CUBESAT MISSION

Adonis Pimienta-Penalver and Sun Hur-Diaz*

A low-thrust lunar CubeSat mission has been proposed to satisfy the requirements of NASAs CubeQuest Challenge. Due to mission and system-imposed limitations, the proposed nominal trajectory encompasses several orbital regimes, such as a fast lunar flyby, long-duration interplanetary coast arcs, and a slow spiral down into a stable lunar orbit, each of which calls for a distinct tracking approach. This paper presents a preliminary evaluation of the orbit determination requirements of each of the stages of the nominal trajectory using the batch filter and measurement type modeling capabilities in NASAs General Mission Analysis Tool (GMAT) software. [View Full Paper]

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AAS 17-667

FRINGE FITTING FOR DOR TONES IN GEODETIC VLBI

S. T. Han,[*] Z. K. Zhang,[†] G. S. Tang[‡] and J. S. Ping[§]

Spacecraft is usually equipped with DOR transponder to support high accuracy interferometric tracking. Some space agencies, such as ESA/NASA, adopt correlator based on phase locking or local correlation algorithm to process DOR tones. While geodesy and astronomy agencies usually deploy correlator and post-processing software (HOPS / AIPS), mainly for quasar observation. As single tone spectrum is totally different from quasar continuum spectrum, here comes the problem: is the fringe fitting still effective for DOR tones signal? In this paper, we discuss the fringe fitting algorithm suitable for DOR tones and make a comparison with experiment data. [View Full Paper]

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AAS 17-669

STATION-KEEPING OF LIBRATION POINT ORBITS WITH SEQUENTIAL ACTION CONTROL TECHNIQUE

Dandan Zheng,[*] Jianjun Luo,[†] Zixuan Xiong[‡] and Jianping Yuan[§]

A new method for L1 libration-point orbit stationkeeping is proposed in this paper. Three-dimensional orbits in the vicinity of the interior libration point (L1) of the Sun-Earth/Moon barycenter system are currently being considered since 1990s. Because such libration point trajectories are, in general, unstable, spacecraft moving on these paths must use some form of trajectory control to remain close to their nominal orbit. The primary goal of this effort is the development of a stationkeeping strategy applicable to such trajectories. In this study, L1 libration-point orbit stationkeeping is studied using Sequential Action Control(SAC), SAC has shown promise in simulation as a closed-loop receding horizon style controller that can compute optimal actions in real-time for nonlinear systems. The controller is designed such that the actual trajectory tracks a predetermined reference orbit with good accuracy. Numerical results employing this method demonstrate the potential of this method. [View Full Paper]

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AAS 17-672

MATHEMATICS USED FOR DEEP SPACE NAVIGATION

James K. Miller* and Gerald R. Hintz†

Navigation of spacecraft requires science and mathematics equations to be programmed onto digital computers. For deep space navigation, the science content is about ten percent and the mathematics content is about 90 percent. Science is here defined as any mathematical expression that is observed and cannot be proved. We start with these science mathematical expressions and other mathematical expressions that are accepted as true by inspection and may be regarded as axiomatic. The mathematics presented here involve manipulation of the given mathematical expressions until we obtain a result that is useful. The equations of motion are a simple example. The resultant derivation is regarded as a proof if the given mathematics are generally accepted as true.

In this paper, a number of derivations are described that are representative of the mathematics that have been used for navigation of spacecraft in deep space, beyond the orbit of the Moon. The selected derivations are by no means complete but emphasize those incorporated in computer algorithms and differ from the conventional mathematics used for obtaining analytic solutions. [View Full Paper]

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AUTONOMOUS PLANNING OF CONSTRAINED SPACECRAFT REORIENTATION MANEUVERS

T. Lippman,[*] J. M. Kaufman[*] and M. Karpenko[†]

Planning attitude constrained spacecraft reorientation maneuvers can be done autonomously by constructing and solving a nonlinear optimal control problem. Attitude constraints, in the form of keep-out or keep-in cones are added as path constraints. Since the control variables do not appear in the path constraint equations, it can be difficult to obtain numerical solutions. In this paper, the constrained spacecraft reorientation problem is solved using guess-free pseudospectral optimal control theory. The behavior of the dual variables, and in particular the path covectors, is studied and some connections between computation and the nature of the dual space is discussed. [View Full Paper]

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PULSAR NAVIGATION: DEFINING AN UPPER BOUND FOR DISTANCE FROM REFERENCE

Stoian Borissov,* Grayson Bridges,† William Vlasak,† Jeffrey Butcher† and Daniele Mortari‡

Pulsar navigation uses signals from distant pulsars to estimate an observer's position relative to a defined reference point. Due to the periodic nature of incoming pulsar signals, the possible locations where a certain pulse pattern can be observed is non-unique. In order to prevent such ambiguous measurements, an upper bound on the distance from the reference point is developed which guarantees a unique position estimate. This paper first explains in detail the problem of ambiguous measurements in pulsar navigation and then derives the upper bound for distance from a reference point. This upper bound is dependent on the pulsar characteristics and defines the size of the "reference volume". An algorithm for calculating size of the reference volume is presented along with a detailed development of how the size is affected by pulse model uncertainty. Finally, example calculations are presented using cataloged pulsars. [View Full Paper]

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AAS 17-690

COMPARATIVE STUDY OF TRACKING CONTROLLERS APPLIED TO MARTIAN AEROCAPTURE

Benjamin W. L. Margolis*[*] and Mohammad A. Ayoubi[†]

In this paper, we present a comparison of three tracking controllers applied to a Martian aerocapture vehicle following an arbitrary trajectory: a Takagi-Sugeno Fuzzy Model (TSFM) based discrete-time model predictive controller (MPC), a TSFM based parallel distributed controller (PDC), and a finite-horizon linear quadratic regulator (LQR). The change in velocity (ΔV) required to bring the orbit of the controlled exit conditions to the orbit of the reference trajectory exit conditions is evaluated over a range of initial condition errors. [View Full Paper]

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AAS 17-707

LOW-THRUST GEO ORBIT TRANSFER GUIDANCE USING SEMI-ANALYTIC METHOD

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

A low thrust GEO orbit transfer guidance is proposed based on the concept of semi-analytic satellite theory. Three weights every segment of the orbital elements of a continuous low thrust transfer are introduced, by changing which, shorter orbit transfer time and corresponding attitude angles of the spacecraft can be obtained. These parameters are computed from the minimum-time transfer employing unscented Kalman filter parameter estimation. This algorithm is simple and effective, to significantly reduce the computation load for the long-duration, many revolution trajectories. A numerical simulation of a GTO-GEO transfer is presented to demonstrate the proposed guidance scheme.

[View Full Paper]

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AAS 17-718

OPERATIONAL EXPERIENCE AND ASSESSMENT OF THE IMPLEMENTATION OF THE MAPLET TECHNIQUE FOR ROSETTA'S OPTICAL NAVIGATION

Francesco Castellini,[*] Ramon Pardo de Santayana,[†] Klaas Vantournhout[‡] and Mathias Lauer[§]

For more than two years, the Rosetta spacecraft successfully navigated around comet 67P, using landmark observations obtained from on-ground daily processing of images from its navigation cameras as main orbit determination observables. Landmark observations were made using a set of small digital elevation and albedo maps, called 'maplets'. This paper describes in details ESOC's maplet implementation, and analyses a vast operational data set (1.146 million observations of 10834 landmarks in 13788 images), assessing the performances and robustness of this technique for optical navigation and showing its relevance in the success of the Rosetta mission. [View Full Paper]

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AAS 17-742

CONJUGATE UNSCENTED TRANSFORMATION BASED APPROACH TO COMPUTE HIGHER ORDER STATE TRANSITION MATRIX FOR NONLINEAR DYNAMIC SYSTEMS: APPLICATIONS TO UNCERTAINTY PROPAGATION

Taewook Lee,[*] Puneet Singla[†] and Manoranjan Majji[‡]

In this paper, Conjugated Unscented Transformation (CUT) based approach is presented to compute higher order state transition matrices in a derivative free manner and a computationally attractive manner. The proposed approach is non-intrusive in nature and is similar to stochastic collocation methods. The connection between stochastic collocation methods, geometric series methods and the conventional higher order state transition matrix approach are discussed. The computed state transition matrices are valid over the desired domain represented by a probability density function rather than valid along a single trajectory of a dynamical system. Benchmark problems corresponding to uncertainty propagation are considered to demonstrate the numerical efficiency and accuracy of the proposed ideas. [View Full Paper]

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AAS 17-771

DECENTRALIZED FUSION WITH FINITE SET STATISTICS FOR LANDING NAVIGATION

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

The simultaneous localization and mapping (SLAM) problem is one that utilizes a vehicle's observations of its environment to refine an estimate of that environment while improving understanding of its own state. This paper proposes the use of SLAM tools formulated using finite set statistics to perform terrain-aided navigation for planetary landers. Further, the methodology is designed to augment, rather than replace, standard extended Kalman filter-based navigation architectures via decentralized fusion with feedback, enabling a SLAM-Fusion procedure with substantially lower development costs than replacing existing approaches altogether. The resulting approach enables significant performance improvements in existing navigation filters with little to no modification of the existing scheme. The theoretical results are supported via simulation of a lunar descent trajectory and the proposed SLAM-Fusion procedure. [View Full Paper]

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AAS 17-800

PERSPECTIVE PROJECTION OF ELLIPSES AND ELLIPSOIDS WITH APPLICATIONS TO SPACECRAFT NAVIGATION

John A. Christian*

The use of cameras for spacecraft navigation has received considerable interest in recent years. Furthermore, such image-based navigation solutions have been proposed for certain aspects of both the absolute navigation and relative navigation problems. Within both of these application domains, it is common to encounter object contours with an elliptical shape. Elliptical arcs occur frequently because both ellipses (or circles) and ellipsoids (or spheres) appear as an ellipse in an ideal image formed by perspective projection (i.e. the pinhole camera model). This paper investigates this concept in detail and a number of important scenarios are considered. [View Full Paper]

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AAS 17-811

OPTIMIZATION OF IMPULSIVE EUROPA CAPTURE TRAJECTORIES USING PRIMER VECTOR THEORY

Kevin A. Bokelmann* and Ryan P. Russell†

The optimization of impulsive, three-dimensional transfer trajectories to capture at Europa is investigated. Primer vector theory is utilized to determine the number of impulses, and for the gradient information needed to optimize the problem. Two initial boundary conditions are considered: a halo orbit in the vicinity of Europa, and a resonant orbit around Jupiter. Optimization of previously generated, near-optimal halo-to-capture transfers verifies that the predicted minimum ΔV is a good initial measure of optimality. Conversely it is found that the primer vector history is not a useful proxy for optimality for highly sensitive orbits. For the resonant boundary scenario, a new 3D periodic orbit is generated that incorporates natural transfers between a resonant orbit and a halo orbit. The intermediate halo orbit enables phase-free connection of the capture and resonant orbits. The highly-sensitive end-to-end transfer converges to a quasi-ballistic, manifold-like trajectory. [View Full Paper]

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AAS 17-831

PRECISION FORMATION FLYING AND SPACECRAFT POINTING USING PLASMONIC FORCE PROPULSION

Pavel Galchenko* **and Henry Pernicka†**

Precision formation flying and spacecraft pointing for swarm mission concepts requires micropropulsion technologies and robust control solutions. Plasmonic force propulsion can provide nanonewton levels of thrust with which some spacecraft control can be realized. This study considers the feasibility of providing precision pointing and orbit control using an array of plasmonic force thruster configurations within the constraints of system level design requirements of the CubeSat platform (with applicability to micro/nano/pico-satellites in general). Results show that pointing and relative position can be maintained for a range of swarm precision formation flight missions. [View Full Paper]

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AAS 17-835

ORBIT TRANSFER TRAJECTORY DESIGN USING FINITE-BURN MANEUVER UNDER STEERING-ANGLE CONSTRAINTS

Donghun Lee,[*] Dong-Hyun Cho,[*] Young-Joo Song,[*] Su-Jin Choi,[†] John Carrico[‡] and Mike Loucks[‡]

An orbit transfer problem using finite-burn maneuvers without or under a constraint on steering-angle of the thruster is considered. The time history of steering-angle is important in order to minimize delta-V loss for a finite burn maneuver. In this paper, the steering-angle profiles are designed both in the inertial reference frame and rotating frame, respectively. In addition, steering-angle profiles such as anti-velocity direction is also investigated, which can be applicable to a real space exploration mission. As an example, an intermediate orbit design problem with finite-burn maneuvers is explained, and the results are presented. The performance with each steering-angle profile will be presented to compare the performance each other. [View Full Paper]

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PROXIMITY OPERATIONS

Session Chair:

Session 23: Jacob Darling

The following papers were not available for publication:

AAS 17-716 Paper Withdrawn

AAS 17-839 Paper Withdrawn

AAS 17-574

NAVIGATION SYSTEM AND TRAJECTORY ANALYSIS FOR ACTIVE DEBRIS REMOVAL MISSION

Naomi Murakami* and Toru Yamamoto†

The key to realizing a safe approach toward such non-cooperative targets as on-orbit debris is building a robust navigation system. However, non-cooperative targets lack any means to actively assist in relative measurement, thus making it difficult to realize robust navigation. And because debris removal missions must be cost-effective, the removal satellite is likely to lack sufficient resources. Thus, effective navigation sensors and other means are limited. In order to examine the feasibility of debris removal missions, the navigation requirements for a safe approach must be clarified. Linear Covariance Analysis (LCA) is a powerful method of examining the applicability of a designed system, especially at an early study phase. By providing various navigation sensor errors and examining trajectory dispersions, the required levels of sensor performance can be obtained. In this study, we designed a navigation system and an approach trajectory for debris removal missions, and examined trajectory safety using LCA. At the same time, we conducted a case study on the performance provided by different sensors and derived possible navigation requirements. [View Full Paper]

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AAS 17-665

HOVERING ORBIT CONTROL BASED ON CONTINUOUS THRUST

Yinrui Rao,* Ran Zhang† and Chao Han‡

The region hovering orbit formed by periodic impulse control has been concerned in recent years. Applicability of the impulsive control approach is limited because of its high fuel consumption. In this study, the hovering orbit control problem based on continuous thrust is exhaustively researched. Based on the Gaussian perturbed equation, an analytic constant continuous thrust control strategy for hovering orbit is derived. With the proposed method, the fuel consumption for hovering orbit control can be effectively reduced. The effect of the control points on the required thrust is analyzed. Numerical simulations are conducted to demonstrate the proposed method's efficacy. [View Full Paper]

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AAS 17-733

PRELIMINARY GN&C DESIGN FOR THE ON-ORBIT AUTONOMOUS ASSEMBLY OF NANOSATELLITE DEMONSTRATION MISSION

Jing Pei,* Matt Walsh,† Carlos Roithmayr,‡ Chris Karlgaard,§ Mason Peck** and Luke Murchison††

Small spacecraft autonomous rendezvous and docking (ARD) is an essential technology for future space structure assembly missions. The On-orbit Autonomous Assembly of Nanosatellites (OAAN) team at NASA Langley Research Center (LaRC) intends to demonstrate the technology to autonomously dock two nanosatellites to form an integrated system. The team has developed a novel magnetic capture and latching mechanism that allows for docking of two CubeSats without precise sensors and actuators. The proposed magnetic docking hardware not only provides the means to latch the CubeSats, but it also significantly increases the likelihood of successful docking in the presence of relative attitude and position errors. The simplicity of the design allows it to be implemented on many CubeSat rendezvous missions. Prior to demonstrating the docking subsystem capabilities on orbit, the GN&C subsystem should have a robust design such that it is capable of bringing the CubeSats from an arbitrary initial separation distance of as many as a few thousand kilometers down to a few meters. The main OAAN Mission can be separated into the following phases: 1) Launch, checkout, and drift, 2) Far-Field Rendezvous or Drift Recovery, 3) Proximity Operations, 4) Docking. This paper discusses the preliminary GN&C design and simulation results for each phase of the mission.

[View Full Paper]

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AAS 17-753

SIMULATED FORMATION CONTROL MANEUVERS FOR THE RANGE CUBESAT MISSION

Daniel Groesbeck,* Brian C. Gunter† and Kenneth Hart*

The Ranging And Nanosatellite Guidance Experiment (RANGE) mission will fly two 1.5U CubeSats in a leader-follower formation, using only differential drag to control their relative separation distance. To prepare for mission operations, a simulation was developed that involved the creation of a high-precision orbit propagation (HPOP) plugin for AGI's Systems Tool Kit (STK) that accounts for rarefied flow characteristics and incorporates a maneuver control system. To evaluate the impact of using the rarefied flow model, various scenarios were run in high and low drag modes using the HPOP propagator, with and without the plugin activated. The difference was significant, showing differences at the kilometer level after several days of simulation. This analysis was compared to real mission positioning data from similar missions by Planet and Aerospace Corp. These comparisons allowed for the determination of an upper and lower bound of expected separation rates for RANGE. This enabled the creation of a series of control maneuvers that will be used to maintain a stable (oscillating) orbit configuration for RANGE, as well as for increasing or decreasing the satellites relative distance within a fixed timeframe. [View Full Paper]

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AAS 17-787

AUTONOMOUS GUIDANCE ALGORITHMS FOR FORMATION RECONFIGURATION MANEUVERS

Theodore Wahl* **and Kathleen Howell†**

Spacecraft formations operating autonomously offer the potential to support a wide variety of missions. A proposed autonomous guidance algorithm for formation reconfiguration maneuvers is updated and expanded in this investigation. The guidance algorithm separates the maneuver into two problems: assigning and then delivering the spacecraft. An improved auction process assigns the spacecraft to new positions, and two methods of delivering the spacecraft are examined. One is based on Artificial Potential Function (APF) guidance; alternatively, Model Predictive Control (MPC) guidance is explored. The performance of the guidance algorithm and its constituent pieces are assessed through simulations. [View Full Paper]

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GEOMETRIC CAMERA CALIBRATION USING NEAR-FIELD IMAGES OF THE ISS CENTERLINE DOCKING PLATE

Andrew Rhodes,[*] John Christian[†] and Shane Robinson[‡]

The next generation of spacecraft will be capable of autonomously docking with the International Space Station (ISS) and other space assets. While a variety of sensing solutions exist, camera-based methods are an especially promising option. Achieving these relative navigation objectives, however, requires the camera to be well calibrated. Preflight estimates of the geometric calibration parameters may be available, but on-orbit recalibration may be necessary due to environmental effects. Here, we propose that geometric calibration for a navigation camera may be performed using a collection of images of the ISS's centerline docking plate. Using this object for calibration permits a flexible approach that various spacecraft could use for geometric camera calibration.

[View Full Paper]

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AAS 17-821

ΔV-OPTIMAL RENDEZVOUS MANEUVERS IN CIS-LUNAR HALO ORBITS AROUND EML2

Davide Conte* and David B. Spencer†

This paper presents solution techniques for finding Δv-optimal maneuvers to rendezvous with a target spacecraft in cis-lunar halo orbits around the Earth-Moon Lagrange point 2 (EML2). This family of orbits was chosen due to the rising interest in cis-lunar space for human and robotic exploration. The dynamics and the stability of relative motion in the Circular Restricted Three-Body Problem (CR3BP) are analyzed using Floquet theory. In order to determine optimal maneuvers that the chaser spacecraft needs to accomplish to rendezvous with the target vehicle, simplified models of the relative motion in the CR3BP are explored and utilized, and compared to the full non-linear CR3BP model.

[View Full Paper]

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AAS 17-841

DEVELOPMENT AND VALIDATION OF A GNC ALGORITHM USING A STEREOSCOPIC IMAGING SENSOR IN CLOSE PROXIMITY OPERATIONS

Jill Davis,[*] Pavel Galchenko,[*] Donna Jennings[*] and Henry Pernicka[†]

The stereoscopic imaging system used for conducting proximity operations with an inspector satellite near a noncooperative resident space object is validated using AGI's Systems Tool Kit and the MATLAB environment. The guidance, navigation, and control algorithms of the system are implemented using MATLAB, while an STK scenario acts as the truth model and provides the algorithms with sensor data. STK is also used for the graphical modeling and visualization. The stereoscopic imaging cameras are modeled in STK as conical sensors with specified fields of view. Custom angles created in STK then provide real time bearing angle data to the navigation filter, which determines the position, velocity, and attitude of the inspector satellite and the relative position and velocity of the nRSO using complementary sensor data. These data are also extracted from the STK model through the MATLAB/Connect data provider commands, and include magnetometer, IMU, GPS, and Sun sensor data. [View Full Paper]

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AAS 17-848

COMPUTATIONALLY EFFICIENT METHODS FOR FUEL OPTIMAL PROXIMITY MANEUVERS WITH CONSTRAINTS*

Eric R. Prince,† Ryan W. Carr‡ and Richard G. Cobb§

This paper develops low and high-fidelity models to generate fuel optimal guidance for an inspector satellite operating near a resident space object in geosynchronous orbit. The inspector satellite is assumed to employ an on/off thruster of finite nature, as opposed to using an impulsive burn approximation. The main goal of the inspector satellite in this study is to optimally maneuver into a prescribed natural motion circumnavigation orbit about the resident space object, subject to one of two possible lighting constraints. The first scenario, denoted a hard lighting constraint, ensures the inspector satellite aligns with the sun vector in the relative frame projected into the orbital plane, such that favorable lighting conditions exist throughout the resulting natural motion. The second scenario, denoted a soft lighting constraint, allows an angular margin from the sun vector, such that the satellite is close enough to the sun vector, allowing the maneuver cost to be further minimized. The inspector satellite is assumed to perform a burn-coast-burn sequence, and an analytic propagation of the Hill-Clohessy-Wiltshire states given this finite-burn sequence is used to make the optimization routines computationally efficient. The lower-fidelity model uses this analytic propagation in both a particle swarm algorithm and a nonlinear programming problem solver, where the nonlinear programming problem solver also uses analytic derivative information to assist in finding a solution. These solutions are then fed into the higher-fidelity model, a pseudospectral solver, as an initial guess, to obtain a solution using the general nonlinear equations of relative motion. The nonlinear programming problem solver's performance is analyzed, with recommendations on which specific algorithm to use depending on the lighting constraints.

[View Full Paper]

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SPACEFLIGHT MECHANICS

Session Chair:

Session 25: Andrew Sinclair

AAS 17-552

ATMOSPHERIC DENSITY ESTIMATION WITH LIMITED ORBIT TRACKING DATA

Jinjun Shan* and Yuan Ren*

Inaccurate atmospheric density is the biggest error source in orbit determination and prediction. The commonly used empirical density models, such as Jacchia, NRLMSISE, DTM and Russian GOST, have a relative error of about 10 – 30%. Due to the uncertainty in the atmospheric density distribution, high accuracy estimation of the atmospheric density cannot be achieved by a deterministic model. Calibration of the atmospheric density model using up-to-date orbit tracking data may improve the model accuracy. However, this method has two main drawbacks. The first is that it is difficult to obtain enough suitable orbit tracking data. Sometimes the orbit tracking data is not enough to constitute an overdetermined system for coefficient identification, or the tracked orbits accumulate in a small region and cannot cover the full calibration region. The second is that there are only a limited number of objects that have known ballistic coefficients. Without a known ballistic coefficient, the density information cannot be separated from the orbit tracking data. In this paper, a novel algorithm is developed to calibrate the density model and estimate the unknown ballistic coefficients simultaneously. With the density information from the empirical model, this method can estimate the distribution of the atmospheric density effectively by using the incomplete orbit tracking data. Simulation results show the effectiveness of the proposed calibration algorithm. [View Full Paper]

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AAS 17-610

DEFLECTION ASSESSMENT FOR A GRAVITY TRACTOR SPACECRAFT

Shyam Bhaskaran*

One proposed method to deflect a potential Earth impacting asteroid is via the "gravity tractor" method. Here, a spacecraft, hovering close to an asteroid using ion engines, uses its gravitational pull to change the asteroid's orbit away from an impacting path. The proposed Asteroid Redirect Robotic Mission was slated to demonstrate the feasibility of this technique on the asteroid 2008EV5, and measure the amount of deflection. In this paper, the questions of how long the tractoring needs to be to cause a measurable deflection, and how the spacecraft can be used to measure it were examined. [View Full Paper]

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AAS 17-611

CONVERTING TO PHYSICAL COORDINATES WITH OR WITHOUT A FULL SET OF SENSORS BY EIGEN-DECOMPOSITION OF IDENTIFIED STATE-SPACE MODELS

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

This paper presents a method to convert an identified state-space model of a structure in an unknown and arbitrary coordinates to physical coordinates from which the structure mass, stiffness, and damping matrices can be recovered. The present method overcomes the high dimensionality associated with a Kronecker-based method for high degree-of-freedom systems. A full set of sensors is not required. One sensor or one actuator is required per degree of freedom and at least one collocated pair of sensor and actuator is necessary for unique conversion of the model to physical coordinates. [View Full Paper]

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AAS 17-612

MASS STIFFNESS AND DAMPING MATRICES FROM STATE-SPACE MODELS IN PHYSICAL COORDINATES BY EIGEN-DECOMPOSITION OF A SPECIAL MATRIX

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

This paper presents a method to recover the mass, stiffness, and damping matrices from an identified state-space model of a flexible structure in physical coordinates. The proposed solution is simple and computationally efficient for high degree-of-freedom systems. The method preserves the symmetry of the mass, stiffness, and damping matrices in the presence of noise. Any combination of displacements, velocities, accelerations can be used as measurements. [View Full Paper]

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AAS 17-663

PRELIMINARY STUDY OF THE LUNAR PHYSICAL LIBRATIONS BY VLBI OBSERVATIONS OF CHANG'E-3 LUNAR LANDER

Zhongkai Zhang,[*] Songtao Han[†] and Lan Du[‡]

The successful landing of the Chang'E-3 on the Moon opened up the window for observing the Moon with VLBI again. In this study, the method using VLBI observations of artificial sources on the lunar surface to estimate the Euler angles and lunar librations parameters is described and corresponding formulations are derived. VLBI observations of Chang'E-3 lunar lander were used to preliminarily estimate the Euler angles along with the lander position coordinates. The results showed that the Euler angles can be estimated along with the position coordinates of the lunar lander using the method described and applying the estimated Euler angle corrections could decrease the standard deviations of the lander position coordinates. [View Full Paper]

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USE OF ADVANCED STATISTICAL TECHNIQUES FOR MISSION ANALYSIS: CASE STUDY FROM A GOOGLE LUNAR X TEAM (SPACEIL)

David Shteinman,[*] Zdravetz Lazarov[†] and Yu-Heng Ting[‡]

Lunar X prize teams are competing to be the first non-governmental spacecraft to soft land on the Moon. All the teams have small budgets that are severe restrictions for mission designers. Hence it is necessary to rely heavily on historical data analysis and simulation to characterize and quantify *expected* performance of mission components. Statistical methods such as *Exploratory Data Analysis (EDA)*, *Time Series Analysis* and *Design & Analysis of Computer Experiments* (*DACE*) are ideally suited to the task of delivering maximum information on the operating windows of expected performance at minimum cost. A case study is presented from a Lunar X team (SpaceIL) using statistical methods to characterize the expected performance of the Universal Space Network (USN) tracking stations to be used in the mission, using residuals data from the NASA Lunar Reconnaissance Orbiter mission (LRO). A moving window Time Series method was used to model the occurrence and duration of jumps in residuals. A feature of our method is the ability to isolate transient signals (e.g. jumps) from the usual noise for improved characterization of tracking performance. The EDA process revealed features such as bimodal distribution of data at some stations, and periodic patterns in the autocorrelation between residual values by day and by pass. These actual tracking performance measures will be used as inputs to a simulation tool for performance analysis of SpaceIL's orbit determination capabilities. To maximize the information from the minimum number of simulation runs we outline the use of statistical DACE – a method adapted from industrial experiments that is highly efficient at determining input/output functional relationships in complex multivariate systems. The case study indicates a way forward for increased use of statistical tools and approaches in Mission Design and Analysis, by adapting methods from other disciplines such as econometrics and industrial experimentation. [View Full Paper]

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THE STUDY OF ONLINE LEARNING RECOGNITION METHOD OF THE SPACE TUMBLING NON-COOPERATIVE TARGET BASED ON SMALL SATELLITE PLATFORM

Xiong Zixuan,[*] Feng Dongzhu,[†] Yu Hang,[‡]
Wang Zexiang,[*] Wen Tongge,[*] Li Xinfang[*] and Cao Fuzhi[*]

In most space scenarios, the object to be detected is unknown in advance, and there is no prior knowledge. In other words, the target is arbitrary and only specified at runtime, which leads to trouble tracking to account for the scale changes and spinning during object motion, lighting conditions and occlusion. Arbitrary targets now are widely tracked by adaptive tracking-by-detection methods in computer vision. And the recognition problems are treated as classification task. By online learning, the classifiers can update the object model for better recognition result. For a high accuracy and real-time recognition, this paper develops a recognition method for the space tumbling non-cooperative target based on small satellite platform. The method is based on a Support Vector Machine algorithm to recognize a space tumbling target. Online learning as a part of the algorithm improves the accuracy of recognition. A simulation system is established based on C++/STK to verify the validity and evaluate the performance of the proposed algorithm. With comparisons of 3 different recognition algorithms, the conclusion is that the tumbling non-cooperative target can be accurately recognized and tracked on real-time by taking the advantage of the proposed algorithm. [View Full Paper]

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TIMING COEFFICIENT AND SOLAR LUNAR PLANETARY EPHEMERIS FILES VALID OVER VERY LONG TIME INTERVALS AND THEIR APPLICATION IN NUMERICAL AND SEMIANALYTICAL ORBIT PROPAGATION

Zachary Folcik* and Paul J. Cefola†

Time differences and solar, lunar, and planetary (SLP) ephemeris data are used in precision orbit determination applications. The Linux GTDS and DSST Standalone orbit propagator programs use low-degree polynomials to approximate the time differences between the atomic, UTC, and UT1 time systems. Low-degree polynomials also are used for the polar motion parameters. Chebyshev polynomials are used to represent the SLP ephemerides and the rotation matrices. These approximations reduce storage and runtime for orbit propagation and for orbit determination. Previously, representation of 50 years of timing and third body positional data has been demonstrated. The current work reproduces the timing coefficient and SLP files using a Linux version of the TRAMP program and extends the time duration of these files to 200 years. [View Full Paper]

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AAS 17-683

POISSON-DARBOUX PROBLEM'S EXTENDED IN DUAL LIE ALGEBRA

Daniel Condurache*

The main goal of this research is the development of a new approach of Poisson-Darboux problem solution in dual Lie algebra. Using the isomorphism between the Lie group of the rigid displacements $S\mathbb{E}_3$ and Lie group of the orthogonal dual tensors $\underline{S\mathbb{O}_3}$ a new solution of this problem is given by recovering the rigid motion knowing its twist. The solution is the replica of the classical Poisson-Darboux problem in the algebra of dual numbers. The results are applied for giving a representation theorem of the six degrees of freedom relative orbital motion problem. Using the n-th order Cayley transformation of dual vectors, the minimal representation of this problem is obtained. The novelty of the method over existing solutions is discussed and the main advantages are revealed.

[View Full Paper]

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AAS 17-780

USING SPHERICAL HARMONICS TO MODEL SOLAR RADIATION PRESSURE ACCELERATIONS

Ariadna Farrés,[*] Dave Folta[†] and Cassandra Webster[‡]

Solar Radiation Pressure (SRP) is the acceleration produced by the impact of the photons emitted by the Sun on the surface of a satellite. The incident photons are absorbed and reflected by the different components on the satellite's surface, where the rate of absorption and reflection depends on the properties of the satellite's surface material. The acceleration produced by SRP plays an important role on the design and navigation of Libration Point Orbits and interplanetary trajectories. In this paper we introduce an alternative way to obtain high fidelity models for the SRP acceleration using a Spherical Harmonic approximation. [View Full Paper]

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HUMAN MISSIONS BEYOND EARTH ORBIT

Session Chair:

Session 26: Raymond Merrill

AAS 17-577

LOW EXCESS SPEED TRIPLE CYCLERS OF VENUS, EARTH, AND MARS

Drew Ryan Jones,* Sonia Hernandez* and Mark Jesick*

Ballistic cycler trajectories which repeatedly encounter Earth and Mars may be invaluable to a future transportation architecture ferrying humans to and from Mars. Such trajectories which also involve at least one flyby of Venus are computed here for the first time. The so-called triple cyclers are constructed to exhibit low excess speed on Earth-Mars and Mars-Earth transit legs, and thereby reduce the cost of hyperbolic rendezvous. Thousands of previously undocumented two synodic period Earth-Mars-Venus triple cyclers are discovered. Many solutions are identified with average transit leg excess speed below 5 km/sec, independent of encounter epoch. The energy characteristics are lower than previously documented cyclers not involving Venus, but the repeat periods are generally longer. [View Full Paper]

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AAS 17-586

OPERATIONAL ASPECTS AND LOW THRUST TRANSFERS FOR HUMAN-ROBOTIC EXPLORATION ARCHITECTURES IN THE EARTH-MOON SYSTEM AND BEYOND

Florian Renk,[*] Markus Landgraf[†] and Max Roedelsperger[‡]

In the frame of the International Space Exploration Coordination Working Group (ISECG) the European Space Agency is participating in the planning of future exploration architectures. This participation also puts new challenges on the mission analysis of such architectures, since the mission analysis for an exploration architecture design is significantly different from the one of a single mission design. E.g. vehicles are usually staged, rendezvous and docking possibility significantly increases the trade space between different options. This also changes the operational aspects for these architectures compared to single spacecraft robotic science missions. While many orbit types in the Earth-Moon system as e.g. Low Lunar Orbits (LLO), Lissajous and Halo Libration Point Orbits (LPO), Distant Retrograde Orbits (DRO) or Nearly Rectilinear Orbits (NRO) as well as the associated transfer scenarios are well studied from a theoretical point of view, this paper will focus on the operational aspects to fly missions towards these destinations and to operate them there. This will include the discussion on the availability of transfer windows, availability of communication links, orbit determination requirements as well as the requirements for the rendezvous of spacecraft far from Earth or the treatment of contingency scenarios. Especially the latter point is of interest, since e.g. the libration point orbits are inherently unstable and thus recovery scenarios in case of e.g. missed station-keeping manoeuvres or unforeseen accelerations must be defined and considered in the operational scenario. A further aspect in the paper will be the operational requirements for the transfer of the exploration infrastructure hub between the different destinations to optimally support the various envisioned exploration missions (e.g. lunar surface access, interplanetary departure to an asteroid, servicing of Sun-Earth Libration Point observatories). These transfers are required, since none of the available orbit options is optimal for all exploration mission scenarios. Since the initial exploration hub will only be man-tended, the transfers between different orbits are not required to be fast, but the hub can use either low energy transfers or e.g. solar electric propulsion (SEP) for the orbit manoeuvres in order to reduce the required propellant mass and thus reduce logistic costs.

[View Full Paper]

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AAS 17-630

SINGLE CYCLER TRAJECTORIES FOR MARS EXPLORATION

Buzz Aldrin,[*] Brian D. Kaplinger,[†] Anthony Genova,[‡] Robert Potter,[§] Alec Mudek,[§] Archit Arora,[§] Sarag Saikia[**] and James M. Longuski[††]

This paper presents several options for symmetric Earth-Mars cycling trajectories that could be conducted using a single cycler vehicle. Current cycling architectures propose at least two vehicles in order to ensure both short Earth-Mars and Mars-Earth deep space travel time. The options presented include both countable ballistic solutions as well as continuous families of ballistic and near-ballistic (< 50 m/s/period) solutions. Representative trajectories from the initial ballistic and near-ballistic solution sets from a circular-coplanar model are demonstrated, and a mission timeline utilizing this type of trajectory is proposed. [View Full Paper]

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AAS 17-643

A FIRST LOOK AT THE NAVIGATION DESIGN AND ANALYSIS FOR THE ORION EXPLORATION MISSION 2

Chris D'Souza* and Renato Zanetti†

This paper will detail the navigation and dispersion design and analysis of the first Orion crewed mission. The optical navigation measurement model will be described. The vehicle noise includes the residual acceleration from attitude deadbanding, attitude maneuvers, CO_2 venting, waste-water venting, ammonia sublimator venting and solar radiation pressure. The maneuver execution errors account for the contribution of accelerometer scale-factor on the accuracy of the maneuver execution. Linear covariance techniques are used to obtain the navigation errors and the trajectory dispersions as well as the DV performance. Particular attention will be paid to the accuracy of the delivery at Earth Entry Interface and at the Lunar Flyby. [View Full Paper]

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AAS 17-648

HYPERBOLIC ABORT OPTIONS FOR HUMAN MISSIONS TO MARS

B. Aldrin,[*] P. Witsberger,[†] R. Potter,[‡] J. Millane,[§] S. Saikia,[**] B. Kaplinger[††] and J. Longuski[‡‡]

Cycler trajectories have become an important component of Earth-to-Mars transportation systems. A salient feature of such trajectories is the necessity of achieving hyperbolic rendezvous, a requirement that if not met can result in loss of crew. The concept of hyperbolic rendezvous has been met with skepticism. In this paper, we review standard methods for hyperbolic rendezvous and introduce some new approaches that allow for improved abort options. The abort options considered also apply to human missions to Mars that do not involve cycler trajectories. [View Full Paper]

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AAS 17-652

LOW-THRUST TRAJECTORY MAPS (BACON PLOTS) TO SUPPORT A HUMAN MARS SURFACE EXPEDITION

Ryan C. Woolley,* John D. Baker,† Damon F. Landau‡ and Kevin E. Post§

Planning the logistics of multiple launches to support a Mars surface expedition requires good trajectory design tools. Traditional ballistic transfers are well characterized by performance maps known as porkchop plots. However, the transportation of cargo can benefit from the use of low-thrust solar electric propulsion, both in terms of mass delivered and the flexibility of flight durations and dates. This paper describes the design and use of bacon plots (the low-thrust analog to porkchop plots) and their application to the architectural design of a human Mars surface expedition. [View Full Paper]

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AAS 17-826

STATIONKEEPING AND TRANSFER TRAJECTORY DESIGN FOR SPACECRAFT IN CISLUNAR SPACE

Diane C. Davis,* Sean M. Phillips,† Kathleen C. Howell,‡
Srianish Vutukuri§ and Brian P. McCarthy§

NASA's Deep Space Gateway (DSG) will serve as a staging platform for human missions beyond the Earth-Moon system and a proving ground for inhabited deep space flight. With a Near Rectilinear Halo Orbit (NRHO) serving as its primary long-term orbit, the DSG is planned to execute excursions to other destinations in cislunar space. The current study explores the details of generating NRHOs in high-fidelity force models. It then investigates the cost of stationkeeping the primary and destination orbits. Finally, Poincaré maps are employed in a visual design process for preliminary transfer design between candidate orbits in cislunar space. [View Full Paper]

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STUDENT DESIGN COMPETITION

Session Chair:

Session 2: Daniel Scheeres

AAS 17-621

THE ASTRODYNAMICS RESEARCH GROUP OF PENN STATE (ARGOPS) SOLUTION TO THE 2017 ASTRODYNAMICS SPECIALIST CONFERENCE STUDENT COMPETITION

Jason A. Reiter,* Davide Conte,* Andrew M. Goodyear,* Ghanghoon Paik,* Guanwei He,* Peter C. Scarcella,* Mollik Nayyar* and Matthew J. Shaw*

We present the methods and results of the Astrodynamics Research Group of Penn State (ARGoPS) team in the 2017 Astrodynamics Specialist Conference Student Competition. A mission (named Minerva) was designed to investigate Asteroid (469219) 2016 HO3 in order to determine its mass and volume and to map and characterize its surface. This data would prove useful in determining the necessity and usefulness of future missions to the asteroid. The mission was designed such that a balance between cost and maximizing objectives was found. [View Full Paper]

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AAS 17-744

THE NEAR-EARTH ASTEROID CHARACTERIZATION AND OBSERVATION (NEACO) MISSION

Chandrakanth Venigalla,[*] Nicola Baresi,[*] Jonathan Aziz,[*] Benjamin Bercovici,[*] Gabriel Borderes Motta,[†] Daniel Brack,[*] Josué Cardoso dos Santos,[†] Andrew Dahir,[*] Alex B. Davis,[*] Stijn De Smet,[*] JoAnna Fulton,[*] Nathan Parrish,[*] Marielle Pellegrino[*] and Stefaan Van wal[*]

The Near-Earth Asteroid Characterization and Observation (NEACO) mission proposes to explore the fast-rotating asteroid (469219) 2016 HO_3 with a SmallSat spacecraft and perform an early scientific investigation to enable future, more in-depth missions. The NEACO spacecraft is equipped with a low-thrust, solar electric propulsion system to reach its target within two years, making use of an Earth gravity assist. Its instrument suite consists of two optical cameras, a spectrometer, an altimeter, and an explosive impactor assembly. Upon arrival at HO_3, NEACO uses pulsed plasma thrusters to hover, first at a high altitude of 50 km to perform lit surface mapping and shape modeling, and later at a lower altitude of 10 km to refine these models and perform surface spectroscopy. Following the hovering phases, the spacecraft performs several flybys with decreasing periapses in order to estimate the asteroid's mass. Finally, NEACO uses an additional flyby to release an explosive impactor that craters the asteroid surface. After spending a few weeks at a safe hovering distance, the spacecraft returns and images the crater and freshly exposed sub-surface material. This provides information on the strength of the asteroid surface. The science operations are completed within eight months, with the total mission lasting less than three years. The objectives met by the NEACO mission satisfy all science goals for the student competition of the 2017 AAS Astrodynamics Specialist Conference. [View Full Paper]

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AAS 17-754

THE FRONTIER MISSION DESIGN DOCUMENT

Jigisha Sampat,[*] Yufeng Luo,[*] Jasmine Thawesee[*] and Isabel Anderson[*]

The recently discovered small asteroid by the name 2016 HO3 is known to be a companion to Earth while it orbits around the sun. The asteroid has a very similar orbit to Earth's and has been a stable quasi-satellite of the Earth for over a century and will continue to follow this pattern for centuries to come. Although it has been around for so long, it only came to our notice very recently and hence, very little is known to us about this satellite.

The Frontier satellite mission aims to study 2016 HO3's spectral properties, map its surface, and create a global shape model. The satellite uses Lambert's equations of orbital relative motion to travel along the asteroid in its orbit around the sun while mapping it from different directions. While staying outside the field of influence of the asteroid, the satellite will be able to map its surface at 10 m2 resolution. It will also be able to provide input on the morphology of the planet, its surface composition, overall size, and shape and spin characteristics. [View Full Paper]

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NEO: MISSION PROPOSAL FOR ASTEROID (469216) 2016 HO3

Matthew Heacock,* Katherin Larsson,*
Matthew Brandes* and Nathan McIntosh*

The satellite mission concept was developed in response to the AAS/AIAA Student Competition request for the 2017 Astrodynamics Specialist Conference. The competition asked for a small satellite mission to Asteroid (469219) 2016 HO3, henceforth referred to as Asteroid HO3, that could be a secondary payload with the intention to observe and collect data about the asteroid, that lies in a quasi-orbit about the Earth. The satellite mission was developed to satisfy Goals 3, 4, 5 and 7 from the problem statement. In addition to the above given goals, NEO will be primarily composed of off the shelf parts to demonstrate the ability to design science missions with a low barrier to entry and reduce risk. NEO must also be less than 140 kg wet mass and shall fit on an ESPA ring.

[View Full Paper]

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AAS 17-817

FORTUNE: A MULTI-CUBESAT, NEAR-EARTH ASTEROID PROSPECTING MISSION

J. R. Elliott,[*] E. Shibata,[†] P. A. Witsberger,[†‡] J. L. Pouplin,[†] R. J. Rolley,[†] P. Podesta[†] and J. D. Ianev[§]

Asteroids present a unique resource gathering opportunity, since materials gathered from the asteroid do not need to be launched from the Earth's surface. Potential resources include metals for construction purposes and water for fuel. Recently discovered asteroid 2016 HO3 resides in a quasi-orbit about Earth, making it an attractive target for asteroid mining purposes. In this paper we present a multi-CubeSat mission for prospecting and assessing 2016 HO3's potential for resource mining. The mission consists of a 12U CubeSat orbiter that will image the asteroid in the visible wavelengths. X-ray and near-infrared spectra will be obtained. In addition to the orbiter, a 12U impactor system will deliver a 1.35U copper impactor approximately 37 days after the orbiter's arrival. The orbiter will observe the impact, study the resulting crater, and take spectra of subsurface material excavated during the impact. An analogy-based cost model was developed, and mission cost was found to be $38 million in FY17$. [View Full Paper]

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HO3 ASTEROID RENDEZVOUS EXPLORER – H.A.R.E.

Matthew Austin,[*] Larissa Balestrero,[*] Anthony Genova,[*] Fernando Aguirre,[†] Muzammil Arshad,[*] Max Skuhersky,[*] Mathieu Plaisir,[*] Filippo Mazzanti,[*] Nashaita Patrawalla,[†] Joshua Newman,[†] Stephen Sullivan,[*] Tanner Johnson,[*] Connor Nelson[†] and Evan Smith[†]

HO3 Asteroid Rendezvous Explorer (HARE) serves as a prototype for analyzing the characteristics of asteroid 2016 HO3 using a low-mass spacecraft. Primary objectives of this mission include imaging the asteroid, determining its mass and volume over a specific area, measuring the spectral properties of its surface, and measuring surface hardness. HARE outlines how each of these objectives will be met and the spacecraft meets the mass requirement of less than 140 kg. In addition to the spacecraft structure, the trajectory being utilized is thoroughly outlined. [View Full Paper]

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AAS 17-846

BLOCK-LIKE EXPLORER OF A NEAR-EARTH BODY BY ACHIEVING ORBITAL PROXIMITY (BEEBOP)

Kristofer Drozd,[*] Ethan Burnett,[†] Eric Sahr,[‡] Drew McNeely,[‡] Vittorio Franzese[§] and Natividad Ramos Moron[§]

BEEBOP is a remote sensing space mission designed to investigate 2016 HO3, an asteroid recently discovered that lies in a quasi-orbit about the Earth. This mission is designed as a precursor operation such that enough information about 2016 HO3 can be collected so future endeavors to the asteroid, if necessary, will have a higher probability of success. To drive down cost, a 6 U CubeSat with was selected as BEEBOP's spacecraft. Optimal trajectories from Earth to 2016 HO3 were constructed by means of the Calculus of Variations and Indirect Method. Proximity operation trajectories were found by propagating the spacecraft forward in time within a developed model representing the environment around 2016 HO3. The Zero-Effort-Miss/Zero-Effort-Velocity Guidance Algorithm was utilized to maneuver between these trajectories. Lastly, the spacecraft subsystems were formed through multiple iterations until volumetric, mass, power, thermal, and science requirements were met. [View Full Paper]

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POSTER PAPERS

Session Chair:

Session 1: Manoranjan Majji

The following papers were not available for publication:

AAS 17-560 Paper Withdrawn

AAS 17-562 Paper Withdrawn

AAS 17-594 Paper Withdrawn

AAS 17-620 Paper Withdrawn

AAS 17-717 Paper Withdrawn

AAS 17-719 Paper Withdrawn

AAS 17-805 Paper Withdrawn

AAS 17-578

NAVIGATION AUTOMATION FOR THE *SOIL MOISTURE ACTIVE PASSIVE* OBSERVATORY

Robert Haw,[*] Min-Kun Chung,[*] Ram Bhat,[*] Jessica Williams,[†] Maximilian Schadegg[*] and Julim Lee[*]

Soil Moisture Active Passive (SMAP) is a NASA Earth science mission designed to measure soil moisture content and freeze/thaw cycles over a three-year period. This paper presents a 2-year summary of navigation performance, shows navigation compliance (and non-compliance) with Science Orbit Requirements, and describes how automated processes appreciably reduced the size of the navigation team. [View Full Paper]

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LOW THRUST CIS-LUNAR TRANSFERS USING A 40 KW-CLASS SOLAR ELECTRIC PROPULSION SPACECRAFT

Melissa L. McGuire,[*] Laura M. Burke,[†] Steven L. McCarty,[‡] Kurt J. Hack,[§] Ryan J. Whitley,[**] Diane C. Davis[††] and Cesar Ocampo[‡‡]

This paper captures trajectory analysis of a representative low thrust, high power Solar Electric Propulsion (SEP) vehicle to move a mass around cislunar space in the range of 20 to 40 kW power to the Electric Propulsion (EP) system. These cislunar transfers depart from a selected Near Rectilinear Halo Orbit (NRHO) and target other cislunar orbits. The NRHO cannot be characterized in the classical two-body dynamics more familiar in the human spaceflight community, and the use of low thrust orbit transfers provides unique analysis challenges. Among the target orbit destinations documented in this paper are transfers between a Southern and Northern NRHO, transfers between the NRHO and a Distant Retrograde Orbit (DRO) and a transfer between the NRHO and two different Earth Moon Lagrange Point 2 (EML2) Halo orbits. Because many different NRHOs and EML2 halo orbits exist, simplifying assumptions rely on previous analysis of orbits that meet current abort and communication requirements for human mission planning.[1] Investigation is done into the sensitivities of these low thrust transfers to EP system power. Additionally, the impact of the Thrust to Weight ratio of these low thrust SEP systems and the ability to transit between these unique orbits are investigated. [View Full Paper]

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OVERVIEW OF THE MISSION DESIGN REFERENCE TRAJECTORY FOR NASA'S ASTEROID REDIRECT ROBOTIC MISSION

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The National Aeronautics and Space Administration's (NASA's) recently cancelled Asteroid Redirect Mission was proposed to rendezvous with and characterize a 100 m plus class near-Earth asteroid and provide the capability to capture and retrieve a boulder off of the surface of the asteroid and bring the asteroidal material back to cislunar space.[1] Leveraging the best of NASA's science, technology, and human exploration efforts, this mission was originally conceived to support observation campaigns, advanced solar electric propulsion, and NASA's Space Launch System heavy-lift rocket and Orion crew vehicle. The asteroid characterization and capture portion of ARM was referred to as the Asteroid Redirect Robotic Mission (ARRM) and was focused on the robotic capture and then redirection of an asteroidal boulder mass from the reference target, asteroid 2008 EV_5, into an orbit near the Moon, referred to as a Near Rectilinear Halo Orbit where astronauts would visit and study it. The purpose of this paper is to document the final reference trajectory of ARRM and the challenges and unique methods employed in the trajectory design of the mission. [View Full Paper]

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LUCY: NAVIGATING A JUPITER TROJAN TOUR

Dale Stanbridge,[*] Ken Williams,[*] Bobby Williams,[*] Coralie Jackman,[*] Harold Weaver,[†] Kevin Berry,[‡] Brian Sutter[§] and Jacob Englander[‡]

In January 2017, NASA selected the Lucy mission to explore six Jupiter Trojan asteroids. These six bodies, remnants of the primordial material that formed the outer planets, were captured in the Sun-Jupiter L4 and L5 Lagrangian regions early in the solar system formation. These particular bodies were chosen because of their diverse spectral properties and the chance to observe up close for the first time two orbiting approximately equal mass binaries, Patroclus and Menoetius. KinetX, Inc. is the primary navigation supplier for the Lucy mission. This paper describes preliminary navigation analyses of the approach phase for each Trojan encounter. [View Full Paper]

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AAS 17-671

FEATURES AND CHARACTERISTICS OF EARTH-MARS BACON PLOTS

Robert Potter,[*] Ryan Woolley,[†] Austin Nicholas[‡] and James Longuski[§]

Solar electric propulsion (SEP) uses low-thrust trajectories to deliver larger payloads compared to conventional ballistic trajectories. In this paper, we discuss the uses and insights provided by a relatively new mission design tool, the bacon plot, for Earth to Mars trajectories. The bacon plot is analogous to ballistic porkchop plots but for low-thrust missions and helps to visualize many parameters important to low-thrust missions such as delivered payload, maximum and minimum heliocentric distance, propellant requirements, launch window size, and required times of flight. A design scenario for a Mars SEP orbiter is presented to illustrate how mission designers use bacon plots. We also present a new tool that allows for the fast and easy estimation of a SEP spacecraft's optimal power, thrust, trajectory, and required propellant, through the use of a bacon plot estimator that can be run in seconds instead of hours. [View Full Paper]

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AAS 17-674

IMPROVEMENTS TO A HIERARCHICAL MIXTURE OF EXPERTS SYSTEM USED FOR CHARACTERIZATION OF RESIDENT SPACE OBJECTS

Elfego Pinon III,[*] Jessica Anderson,[†] Angelica Ceniceros,[‡] Brandon Jones,[§] Ryan Russell,[**] Noble Hatten[††] and Nicholas Ravago[‡‡]

Part of the Space Situational Awareness (SSA) problem involves detecting, tracking, identifying and characterizing resident space objects (RSOs). Emergent Space Technologies, Inc. has conducted SSA research, sponsored by the Air Force Research Laboratory (AFRL), focused on the use of Hierarchical Mixtures of Experts (HMEs) to process simulated electro-optical measurements to determine RSO characteristics such as attitude profile, size, and shape. This paper discusses recent efforts to improve the performance of the HME by integrating it with advanced bidirectional reflectance distribution function (BRDF) models, a finite set statistics (FISST) based algorithm for detecting and tracking RSOs, and advanced propagators. Test results using simulated observation data are presented. [View Full Paper]

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AAS 17-680

USING TETHERS TO BUILD A "CAPTURE PORTAL" FOR THE PLANETS

A. F. S. Ferreira,[*] A. F. B. A. Prado,[†] A. D. Guerman,[‡] D. P. S. Santos,[§] A. Burov[**] and O. C. Winter[††]

Several new applications of space tethers to maneuver spacecrafts have been suggested recently. Some of them are combinations with the sling shot effect used in several interplanetary missions. In one type of this family of applications, the tether is attached to an asteroid to make a rotation of the spacecraft, so giving energy to send it to the exterior planets of the Solar System or beyond. A similar idea is to make the capture of spacecrafts by a planet of the Solar System using tethers fixed on their moons. In both of these proposals, the tether is carried on-board the spacecraft and anchored to the celestial body during the approach phase. Another possibility is to build an "Escape Portal" using a tether permanently fixed in an asteroid to give energy to spacecrafts to go to the outer planets. The present paper explores in more detail a combination of those two proposals to build a "Capture Portal" for the planets. The main idea is to build a permanent structure fixed on one of the moons of a given planet, so that it can be used for an unlimited number of maneuvers. With this goal, this research searches for equilibrium points that can be used to place the above structures. The type of force in the tether and the stability of the points are also considered. The results shown here can give some insights in the problems that appear when building such "Capture Portal". [View Full Paper]

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ANALYTICAL AND STATISTICAL CHARACTERIZATIONS OF THE LONG TERM BEHAVIOR OF A CLOUD OF DEBRIS GENERATED BY A BREAK-UP IN ORBIT

Florent J. Deleflie,[*] Delphine Thomasson,[†] Walid Rahoma,[‡] Alexis Petit[§] and Michel Capderou[**]

This paper provides an analytical formulation of the time required to form a cloud that can be considered as a randomly distributed one around the Earth after a breakup of a satellite. Starting with a set of arbitrary ΔV, we determine typical values of the mean changes of velocity within the cloud that enable to describe the changes induced on the initial orbital keplerian elements. The sensitivity of the approach is investigated, and a comparison with Fengyun-1C TLE data sets is provided. The study is carried out following an analytical approach jointly with a statistical characterization. [View Full Paper]

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AAS 17-702

ANALYSIS OF GEOSTATIONARY SATELLITE CONJUNCTION MONITORING

Yoola Hwang[*] and Byoung-Sun Lee[†]

As geostationary satellites are increasing, the numbers of operating satellites placed at the same or close longitude are growing up. Two Line Elements (TLE) can be easily used to monitor and analyze the satellites located at same or close longitude for collision monitoring. However, TLE in accuracy is not enough to perform maneuver for collision avoidance. In this paper, we monitor the collision risk by calculating the distances between two satellites at each epoch using TLE, operational orbit, and conjunction data message (CDM). In addition, we study the reliability of TLE by comparing the North American Aerospace Defense Command (NORAD) TLE converted to osculating orbit and propagated with the actual operational osculating orbit. We also discuss about the conjunction monitoring differences between NORAD TLE propagated using our dynamic models and Joint Space Operations Center (JSpOC) CDM based on our experiences in the view of the satellite operator. [View Full Paper]

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AAS 17-735

DETERMINING LOCATIONS AND TRANSFERS OF ARTIFICIAL EQUILIBRIUM POINTS IN A DOUBLE ASTEROID SYSTEM

Geraldo Magela Couto Oliveira,* Allan Kardec de Almeida Junior† and Antônio Fernando Bertachini de Almeida Prado‡

In the absence of a solar sail, the traditional Lagrange points L_1 and L_2 are the only equilibrium points near the asteroid 243 Ida, which is located in the asteroid belt. The use of a solar sail in the spacecraft gives new configurations of equilibrium points, which depend on positions and the inclination of the vector normal for the solar sail with respect to the x axis. These new configurations of equilibrium points are the so called artificial equilibrium points (AEP). A solar sail allows a spacecraft to park closer to the body that is the object of study. Besides that, new perspectives for viewing above or below the ecliptic plane can be reached through the use of a solar sail to observe the body from a stationary condition. The main idea of this manuscript is to obtain the new locations of those points and to calculate the costs to transfer a spacecraft between those points, as well as to show some options to minimize those costs. [View Full Paper]

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AAS 17-751

DYNAMICS OF A SPACE TETHER IN BINARY ASTEROIDS

A. F. S. Ferreira,* A. F. B. A. Prado,† A. D. Guerman,‡ D. P. S. Santos,§
A. Burov** and O. C. Winter††

The present paper studies the dynamics of space elevators constructed in double asteroids of the solar system, assuming an irregular shape for both bodies. To make this task, a tether is attached to the surface of one of the asteroids, with a spacecraft attached in the other end. The analysis of the equilibrium points to place the tether and the stability of those solutions are made. The irregularities of the bodies, assumed to be ellipsoids, are described by the coefficients of a spherical harmonic expansion. The coefficients of this expansion are functions of the dimensions of the bodies. The equilibrium conditions are studied by searching for the situations where the forces acting in the spacecraft have a zero resultant, assuming that only the gravity of both irregular bodies are present in the system. The method is applied in the double asteroid systems (3169) Ostro and (90) Antiope, which are synchronous systems. To verify the effects of the irregularities of the bodies in the solutions, calculations are also made assuming that the bodies are spherical.

[View Full Paper]

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AAS 17-752

IMPULSIVE AERO-GRAVITY ASSISTED MANEUVERS IN VENUS AND MARS TO CHANGE THE INCLINATION OF A SPACECRAFT

Jhonathan O. Murcia P.* **and Antonio F. B. A. Prado†**

The impulsive or powered aero-gravity-assisted is an orbital maneuver that combines three basic components: a gravity-assisted with a passage by the atmosphere of the planet during the close approach and the application of an impulse during this passage. The mathematical model used to simulate the trajectories is the Restricted Three-Body Problem including aerodynamic forces. The present paper uses this type of maneuver considering atmospheric drag and lift forces. The lift is applied orthogonal to the initial orbital plane to generate an inclination change in the trajectory of the spacecraft, which are very expensive maneuvers. The lift to drag ratio selected goes up to 9.0, because there are vehicles, like waveriders, designed to have these values. When the spacecraft is located at the periapsis the impulse is applied to increase or decrease the variation of energy given by the aero-gravity-assisted maneuver. The planets Venus and Mars are selected to be the secondary bodies for the maneuver, due to their atmospheric density and strategic location to provide possible use for future missions in the solar system. Results of the numerical simulations show the maximum changes in the inclination obtained by the maneuvers as a function of approach angle and direction of the impulse, lift to drag ratio and ballistic coefficient. In the case of Mars, inclination change can be larger than 13°, and for Venus higher than 21°. The energy and inclination variations are shown for several selected orbits. [View Full Paper]

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AAS 17-764

ON THE USE OF SOLAR RADIATION PRESSURE TO EJECT A SPACECRAFT ORBITING THE ASTEROID 65803 DIDYMOS (1996 GT)

J. B. Silva Neto,* D. M. Sanchez† and A. F. B. A. Prado‡

Asteroids and comets have become the target of space missions. A major goal of future missions is to find solutions that minimize costs. Our study presents the use of solar radiation pressure, by varying the area-to-mass ratio and/or the reflectivity coefficient of the spacecraft, with the goal to assist in the ejection of the spacecraft from an orbit around an asteroid, for a possible return phase to the Earth or to direct the spacecraft to a second target. The asteroid Didymos, which has a small natural moon (Didymoon), is chosen as the focus of the present study, because it is the target of the AIDA mission. The study showed the existence of small but important escape windows from the asteroid using the solar radiation pressure to eject the spacecraft from the system. The results also showed: survival regions between L4 and L5, with small escape regions nearby, a very large natural ejection zone 20 km away from the surface of Didymos, areas of survival near the surface of Didymos caused by resonances and the identification of a chaotic region ranging from approximately 1.2 km to 20 km from the surface of Didymos. [View Full Paper]

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AAS 17-769

COMPARISON OF OPTIMIZERS FOR GROUND BASED AND SPACE BASED SENSORS*

Bryan Little† and Carolin Frueh‡

Optimization based sensor tasking often requires the evaluation of a time dependent cost function. Once the cost function is defined, a fast, reliable evaluation of the optimization scheme is necessary. In this paper three different optimizers (Greedy, Weapon-Target Association, and Ant Colony Optimization) are compared in order to determine their performance in generating observation strategies. The optimizers will be evaluated against both space based and ground based sensor scenarios. Performance will be compared based on the number of objects expected to be observed. Observation strategies for each sensor-optimizer pair will be analyzed. [View Full Paper]

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

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ORBIT PREDICTION UNCERTAINTY OF SPACE DEBRIS DUE TO DRAG MODEL ERRORS

Christoph Bamann* and Urs Hugentobler†

Orbit prediction uncertainty is a crucial product for many debris-related activities such as conjunction analyses and collision avoidance planning. Aerodynamic drag models commonly represent the largest source of uncertainty in low-Earth orbit (LEO). Not only errors in atmospheric density, but also in object shape, attitude, and flow regime result in orbit prediction uncertainty through the drag model. The present work provides an uncertainty analysis of all these components using state-of-the-art atmosphere and CAD object models. Our results give insight into the nature of the individual error models and their relative impact on orbit prediction uncertainty. It shall support modeling drag-induced process noise for typical LEO orbit prediction scenarios of space debris.

[View Full Paper]

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