2019 Astrodynamics Specialist Conference
Portland, ME, August 11-15, 2019

Aug 12, 2019 Hawthorne

Guidance, Navigation & Control I

Chair: Anil Rao, University of Florida

8:00 **AAS 19-663** **Multi-Sensor Management under Information Constraints**
Kirsten Tuggle, The University of Texas at Austin; Maruthi R. Akella, The University of Texas at Austin

Within the modern aerospace domain, there has been a significant increase in the need for operating autonomously and adaptively as well the configurability of rapid, real-time, plug-and-play sensing systems supporting these operations. Even though most applications also enjoy increased computational power, these types of guidance, navigation, and control tasks can quickly overwhelm the ability to process them as the problem complexity increases over time and/or degrees of freedom. The current work offers an efficient algorithm for an information-penalized LQG problem when selections must be made among multiple sensors at each time-step.

8:20 **AAS 19-827** **Uncertainty Analysis of a Generalized Coning Algorithm for Inertial Navigation**
James Brouk, Missouri University of Science and Technology; Kyle DeMars, Texas A&M University

This paper investigates uncertainty propagation through a generalized coning algorithm used for inertial navigation systems. Coned measurements have often been considered uncertain variables as the statistics for raw measurements no longer apply to a coning algorithm's result. Through the error analysis of a coning algorithm, two methods for mapping errors are introduced and an efficient and consistent propagation of state uncertainty is achieved, establishing that the errors in the algorithms need not be uncertain. Monte Carlo simulations reveal that the algorithms are shown to be consistent with typical methods of attitude dead-reckoning in simulations with and without coning motion.

8:40 **AAS 19-621** **Generalized Composite Noncertainty-Equivalence Adaptive Control of Orbiting Spacecraft in Vicinity of Asteroid**
Keum Lee, CatholicKwandong Univ; Sahjendra Singh, University of Nevada Las Vegas

The paper presents composite noncertainty-equivalence adaptive control (NCEA) systems for the orbit control of spacecraft in the vicinity of a uniformly rotating asteroid. First, a generalized composite noncertainty-equivalence adaptive (NCEA) control system - based on the immersion and invariance theory - is developed. Then two additional composite control systems - (i) a NCEA law with gradient-based adaptation, and (ii) a NCEA law with gradient-based and classical adaptation are designed. Numerical results are presented for orbit control aroud 433 Eros and for hovering over Ida asteroid. The results confirm faster convergence of trajectories to manifold by composite systems with gradient adaptation than NCEA law.

9:00 **AAS 19-722** **The Surface Navigation Approach for the Dragonfly Lander**
Benjamin Schilling, Johns Hopkins Applied Physics Laboratory; Benjamin Villac, Johns Hopkins University Applied Physics Laboratory; Douglas Adams, The Johns Hopkins University Applied Physics Laboratory

Dragonfly is one of two New Frontiers mission proposals selected by NASA in 2018 to proceed to Phase A for further study before final selection in Summer 2019. The mission would investigate Titan's habitability and prebiotic chemistry in situ – leveraging the lower gravity and dense atmosphere, an MMRTG-powered octocopter-lander has been proposed. This provides capability to explore widespread locations, offering an immense impact on both the extent of the science campaign, as well as a precedent for future surface exploration. This paper describes the navigation approach and results obtained in the first part of the concept study.

9:20 **AAS 19-687** **A Framework for Scaling in Filtering and Linear Covariance Analysis**
Christopher D'Souza, NASA - Johnson Space Center; Renato Zanetti, University of Texas at Austin; David Woffinden, NASA Johnson Space Center

Scaling is used extensively for numerical optimization and trajectory optimization. Its use in the estimation community is almost nonexistent. This paper creates the framework for practical scaling in space navigation, in general, and linear covariance analysis, in particular.

9:40 **AAS 19-732** **An Analysis of the Theory of Connections Subject to Inequality Constraints**
Hunter Johnston, Texas A&M University; Carl Leake, Texas A&M University; Daniele Mortari, Texas A&M University

The Theory of Connections (ToC) is a powerful mathematical framework that uses constrained expressions to transform constrained problems into unconstrained problems. Until now, the ToC framework only included equality constraints. This paper shows how to extend ToC to problems that have inequality constraints; a type of constraint that shows up in a variety of areas including path planning and optimal control. Moreover, this paper shows how to write ToC constrained expressions for problems that have both equality and inequality constraints. Additionally, simple examples are included to supplement the explanation of the theory.

10:00 Morning Break

10:20 AAS 19-925 ADDRESSING VARYING LIGHTING CONDITIONS WITH APPLICATION TO TERRAIN RELATIVE NAVIGATION

Jonathan Manni, University of Colorado Boulder; Jay McMahon, University of Colorado Boulder; Nisar Ahmed, University of Colorado Boulder

Camera images and their extracted features collected for visual-inertial terrain rel- ative navigation are largely dependent upon lighting conditions. The impact of varying lighting conditions on the performance of feature correlations between simulated lunar basemaps and camera images with differing lighting conditions is assessed. Relationships between feature correlations and light incidence angle and direction are characterized and identified with application to terrain relative navigation on the Moon.

10:40 AAS 19-809 Adaptive, Dynamically Constrained Process Noise Estimation for Autonomous Orbit Determination

Nathan Stacey, Stanford University; Simone D'Amico, Stanford University

This paper introduces two new methods to accurately estimate process noise online for robust orbit determination in the presence of dynamics model uncertainties. Common orbit determination process noise techniques include state noise compensation and dynamic model compensation, which require offline tuning, as well as covariance matching adaptive filtering, which is not dynamically constrained. To overcome these limitations, a novel approach is developed which optimally fuses state noise compensation and dynamic model compensation with covariance matching adaptive filtering. The proposed algorithms are validated through two case studies: an illustrative example and two spacecraft orbiting an asteroid.

11:00 AAS 19-734 An Explanation and Implementation of Multivariate Theory of Connections via Examples

Carl Leake, Texas A&M University; Daniele Mortari, Texas A&M University

The Univariate Theory of Connections (ToC) is a powerful mathematical framework that transforms constrained one-dimensional problems into unconstrained one-dimensional problems. Univariate ToC has found multiple useful applications; the most notable is solving ordinary differential equations by least-squares. This paper extends Univariate ToC to the multivariate case. The resultant framework, called Multivariate ToC, can be used for a multitude of applications, such as solving partial differential equations by least squares. This paper explains Multivariate ToC in detail and provides

simple examples to supplement the explanation of the theory as well as show how it is implemented.

11:20 **AAS 19-645** **Characterization of Candidate Vehicle States for XNAV Systems**

Kevin Lohan, University of Illinois at Urbana-Champaign; Zachary Putnam, University of Illinois at Urbana-Champaign

In this research, we present the evolution of the number of candidate spacecraft positions in a domain given a defined number of pulsars. The infinite set of candidate intersections may be reduced to a finite set of positions by bounding the domain. The number of candidate positions may be further reduced observing additional pulsars or reducing the error in the phase by increasing the observation time. Results indicate taking measurements from more pulsars is more time efficient at increasing candidate separation, relative to improving measurement accuracy of a smaller set of pulsars.

Aug 12, 2019 Rines A

Relative Motion, Formation Flying, Rendezvous and Proximity Operations I

Chair: Simone D'Amico, Stanford University, Alex Sizemore, NRC

8:00 **AAS 19-659** **Monte Carlo Analysis of a Particle Swarm Optimizer of Space-based Receivers for Geolocation Using Heterogeneous TDOA**

David Lujan, University of Colorado Boulder; Alan Lovell; Troy Henderson, Embry-Riddle Aeronautical University

Radio frequency localization is a passive method that can be used to geolocate a stationary radio transmitter. The use of two space-based receivers to accomplish the localization is investigated and optimized. For this method there are no common receiver locations among the generated measurements which defines the set of measurements to be heterogeneous. The purpose of this work is to optimize the receiver locations thereby optimizing their orbital geometry. A particle swarm optimizer is implemented to find the optima. Monte Carlo simulations are performed to find a consistent set of solutions.

8:20 **AAS 19-920** **Sensor Selection Strategies for Satellite Swarm Collaborative Localization**

William Bezouska, University of Southern California; David Barnhart, University of Southern California

A satellite swarm consisting of cooperative satellites permits the joint estimation of swarm state through the fusing of relative pose measurements between individual satellites. This paper presents strategies for the intelligent real-time selection of measurements in order to reduce power, sensor, and computational requirements for such a swarm. These strategies select a subset of the available relative pose measurements between satellite swarm members at each timestep which maximize estimation performance objectives. Simulation results using both simulated noisy measurements as well as vision-based measurements using rendered images and point cloud registration are presented.

8:40 **AAS 19-651** **Desensitized Optimal Attitude Guidance for Differential-Drag Rendezvous**

Andrew Harris, University of Colorado Boulder; Ethan Burnett, University of Colorado Boulder; Hanspeter Schaub, University of Colorado

Growing interest in fuel-constrained small satellites, large Low Earth Orbit (LEO) constellations, and robustness to thruster failure has motivated the use of drag forces for orbit control. This work presents a novel method of achieving differential-drag formation flight using only attitude control and spacecraft geometry while desensitizing the control to uncertainties in atmospheric properties. This work applies and extends the theory of desensitized optimal control to the attitude-driven differential drag problem. The resulting guidance strategy is compared to conventional LQR rendezvous, demonstrating improvements in both accuracy and robustness to atmospheric variations.

9:00 **AAS 19-810** **Second-Order Solution for Relative Motion on Eccentric Orbits in Curvilinear Coordinates**

Matthew Willis, Stanford University; Simone D'Amico, Stanford University; Kyle T. Alfriend, Texas A&M University

A new, second-order solution in curvilinear coordinates is introduced for the relative motion of two spacecraft on eccentric orbits. The second-order equations for unperturbed orbits are derived in spherical coordinates with true anomaly as the independent variable, and solved by the method of successive approximations. A comparison of error trends against eccentricity and inter-spacecraft separation is presented between the new solution and prominent Cartesian, curvilinear, and orbital element-based solutions from the literature. The second-order curvilinear solution offers a thousand-fold improvement in accuracy over the first-order curvilinear solution, and still greater improvement over first- and second-order rectilinear solutions when large along-track separations are present.

9:20 **AAS 19-764** **Precise rendezvous guidance in cislunar orbit via surrogate modelling**

Satoshi Ueda, Japan Aerospace Exploration Agency

This paper presents a precise rendezvous guidance technique in cislunar orbit. We propose a method to predict optimum guidance parameters such as impulse timing by utilizing disturbances as derived from the onboard navigation solution. This method utilizes surrogate modelling approach such as Kriging, polynomial approximation, and generalized linear regression model. The proposed method will be applied to the practical rendezvous scenario in the L2 NRHO, and analysis results are presented based on numerical simulations. The proposed method is significant that it improves the guidance accuracy for a practical rendezvous scenario in the cislunar environment contributing to the Gateway-related missions.

9:40 **AAS 19-610** **Dynamical Issues in Rendezvous operations with Third Body Perturbation**

Giordana Bucchioni, Department of information engineering ; Mario Innocenti, University of Pisa - Department of Information Engineering

The Moon represents the new frontier of space exploration. Therefore, the paper focuses on the formulation of relative 6-DOF equations of motion of two spacecraft: a passive target spacecraft and an active chaser spacecraft. The first is in orbiting around the Moon in a NRHO and the second must perform rendezvous and berthing with the first. The problem is modelled under the hypothesis of Elliptical Restricted Three Body Problem, and the translational-Rotational dynamics are coupled to model the port-to-port motion, both in Euler angles and quaternion formulation. The linearized equations of motions are also provided for the design of GNC.

10:00 Morning Break

10:20 AAS 19-699 Applied Reachability Analysis of Spacecraft Rendezvous With a Tumbling Object

Costantinos Zagaris, Air Force Institute of Technology; Marcello Romano, Naval Postgraduate School

Rendezvous and proximity operations are becoming more complex, requiring autonomy and the use of more sophisticated, computation-based, guidance and control techniques. Implementing such algorithms in an autonomous system raises important questions on maneuver feasibility. In this paper, backward reachability analysis is conducted in order to visualize a set of initial conditions from which a desired rendezvous maneuver is feasible within a given amount of time and control constraints. A roto-translational model of the spacecraft relative motion is derived. An analysis method is proposed, using minimum-time optimal control solutions, to visualize backward reachable sets of this complex dynamic system.

10:40 AAS 19-685 Desensitized Optimal Spacecraft Rendezvous Control with Poorly Known Gravitational and Solar Radiation Pressure Perturbations

Ethan Burnett, University of Colorado Boulder; Andrew Harris, University of Colorado Boulder; Hanspeter Schaub, University of Colorado

Robust rendezvous guidance is implemented in an environment with uncertain dominant gravitational harmonics C20and C22 and poorly-known solar radiation pressure (SRP) effects. The rendezvous control design presumes the availability of a throttled low-thrust propulsion system, which can be achieved by pulsed plasma thrusters. The control minimizes an augmented cost function composed of the traditional Linear Quadratic Regulator (LQR) terms and terms that are quadratic in system sensitivity to multiple unknown dynamical parameters. Results show that there is much closer agreement between the linear designed trajectory and true controlled trajectory using the desensitized control strategy than there is for LQR.

11:00 AAS 19-913 MMS Extended Mission Eclipse Mitigation and Solar Wind Turbulence Science Campaign

Trevor Williams, NASA/Goddard Space Flight Center; Eric Palmer, a.i.

solutions, Inc.; Dominic Godine, ai Solutions, Inc.; Neil Ottenstein, a.i. solutions, Inc.; Jacob Hollister, ai Solutions, Inc.; Babak Vint, a.i. solutions, Inc.

Launch window design for the Magnetospheric Multiscale (MMS) mission ensured that no excessive eclipses would be encountered during the prime mission. However, it was not physically possible to find solutions that would satisfy the eclipse constraints indefinitely: most extended mission years would contain 1-3 eclipses long enough to potentially damage either the MMS spacecraft or its scientific instruments. It was found that raising apogee radius from 25 to 29.34 Earth radii moderated the peak eclipses significantly at relatively low fuel cost. These maneuvers were performed recently, and a science campaign to study turbulence in the solar wind piggy-backed onto it.

Aug 12, 2019 Eastland Ball Room

Session 1: Trajectory Design & Optimization I

Chair: Angela Bowes, NASA LaRC

8:00 **AAS 19-836** **NAVIGATING TO A KUIPER BELT OBJECT: MANEUVER PLANNING ON THE APPROACH TO ULTIMA THULE**

Dale Stanbridge, KinetX Aerospace; Michael Salinas, KinetX Aerospace; Kenneth Williams, KinetX Aerospace, Inc.; Frederic Pelletier, KinetX Inc.; Jeremy Bauman, KinetX Inc.; Joel Fischetti, KinetX Aerospace; Derek Nelson, KinetX, Inc.; Erik Lessac-Chenen, KinetX Aerospace, Inc.; Coralie Adam, KinetX, Inc.; John Pelgrift, KinetX, Inc.; Bobby G. Williams, KinetX, Inc.; Yanping Guo, JHUAPL; Gabe D. Rogers, The Johns Hopkins University Applied Physics Laboratory; Mark Holdridge, Johns Hopkins APL; H. A. Weaver, Johns Hopkins Univ. Applied Physics Lab; Alan Stern, Southwest Research Institute; Cathy Olkin; John Spencer, Southwest Research Institute; Marc Buie, Southwest Research Institute; Simon Porter, Southwest Research Institute

Nearly thirteen years and over 6.5 billion kilometers into its voyage out of the solar system, on January 1, 2019 , the New Horizons spacecraft achieved the milestone of exploring the furthest, most primitive object ever observed up close. With a closest approach distance of just over 3500 km, New Horizons has yielded detailed, high resolution images of the Kuiper Belt Object Ultima Thule. This paper describes the experience of navigating to Ultima Thule over the final year prior to the closest approach. The optimal placement of maneuver opportunities and the challenge of deciding which maneuvers to implement are discussed.

8:20 **AAS 19-733** **Rapid Evaluation of Low-Thrust Transfers from Elliptical Orbits to Geostationary Orbit**

Mason Kelchner, University of Missouri; Craig Kluever, University of Missouri

Orbit transfers to geostationary-equatorial orbit (GEO) will likely use a combination of chemical- and electrical-propulsion stages to strike a balance between transit time and delivered payload mass. Therefore, mission designers need a method for rapidly evaluating low-thrust transfers to GEO. Relying on full trajectory-optimization programs for preliminary studies is not a desirable option due the time associated with optimizing multiple trajectories. This paper develops a technique that rapidly determines the delta-*v* for a low-thrust transfer from an arbitrary elliptical orbit to GEO. We demonstrate our method by presenting a mission design that trades transfer time and payload mass.

8:40 **AAS 19-745** **Endgame Design for Europa Lander: Ganymede to Europa Approach**

Rodney L. Anderson, Jet Propulsion Laboratory/Caltech; Stefano Campagnola, Jet Propulsion Laboratory; Dayung Koh, JPL; Tim McElrath, JPL/Caltech; Robyn Woollands, Jet Propulsion Laboratory

The endgame scenario that was explored in this analysis consisted of the part of the trajectory starting at the last Ganymede flyby and ending at the final Europa approach for the Europa Lander mission concept. The basic design components included computing the phasing for the final Ganymede encounter, computing the required intermediate Europa flybys, determining the required maneuvers to transition between the intermediate resonances, and interfacing with a computed portal prior to the final approach. Additional analyses were performed to connect the trajectory scenarios to particular landing locations. The final trajectories were then converged in the ephemeris model.

9:00 **AAS 19-782** **Homo- and Heteroclinic Connections in the Spatial Solar-Sail Earth-Moon Three-Body Problem**

Jeannette Heiligers, Delft University of Technology

This paper explores the existence of homo- and heteroclinic connections between solar-sail periodic orbits in the Earth-Moon three-body problem. While such connections have been explored extensively in the classical system, the addition of a solar-sail induced acceleration introduces a time-dependency in the dynamics which prevents the use of traditional tools for reducing the dimensionality of the problem (e.g., the Jacobi constant and spatial Poincaré sections). This paper therefore explores the use of solar-sail assisted manifolds, temporal Poincaré sections, and a genetic algorithm approach to achieve the sought-after connections and apply the approach to a range of solar-sail periodic orbits.

9:20 **AAS 19-779** **Interplanetary Low-Thrust Design Using Proximal Policy Optimization**

Daniel Miller, Massachusetts Institute of Technology; Jacob Englander, NASA Goddard Space Flight Center; RICHARD LINARES, Massachusetts Institute of Technology

This paper aims to demonstrate a reinforcement learning technique for developing complex, decision-making policies capable of planning interplanetary transfers. Using Proximal Policy Optimization (PPO), a neural network agent is trained to produce a closed-loop controller capable of transfers between Earth and Mars. The agent is trained in an environment that utilizes a medium fidelity solar electric propulsion model and a real ephemeris model of the Earth and Mars. The results are compared against those generated by the Evolutionary Mission Trajectory Generator (EMTG) tool.

9:40 **AAS 19-883** **Missed-Thrust Analysis of BepiColombo's Interplanetary Transfer to Mercury Orbit**

Pablo Muñoz, European Space Agency

After its successful launch on October 20th 2018, the BepiColombo mission will spend seven years in interplanetary cruise in order to reach Mercury orbit by means of nine planetary gravity assists (Earth, Venus and Mercury) and extensive usage of its solar-electric propulsion. In preparation for the autumn-2018 launch period, a missed-thrust analysis of BepiColombo's interplanetary transfer was carried out to evaluate the robustness of the reference trajectory against contingency thrust outages. This paper describes the assumptions, methodology, implementation choices and results of this analysis, as well as the derived conclusions, trajectory modifications and recommendations for BepiColombo flight operations.

10:00 **Morning Break**

10:20 **AAS 19-694** **Through the Looking Glass: Mission Design using Interactive and Immersive Visualization Environments**

Jeffrey Stuart, Jet Propulsion Laboratory; Amos Byon, Jet Propulsion Laboratory; Alexander Menzies, Jet Propulsion Laboratory; Try Lam, Jet Propulsion Laboratory; Brent Buffington, NASA / Caltech JPL; Sonia Hernandez, Jet Propulsion Laboratory

Mission design and trajectory analysis is an intensive process requiring advanced computational resources, expert human intuition, and many successive human-in-the-loop iterations to converge on acceptable trajectory designs. One approach to alleviate this burden is through the judicious application of visually interactive environments that allow intuitive human assessment and real-time updates as options are explored. In this investigation we will specifically focus on the challenges presented in the early- to mid-development phases of a mission, where these phases are characterized by (sometimes rapid) shifts in mission objectives, spacecraft architecture, and concept of operations as trade spaces are explored.

10:40 **AAS 19-675** **Theory of Connections applied to nonlinear programming under equality constraints**

Daniele Mortari, Texas A&M University; Yalchin Efendiev, Texas A&M University

This paper introduces an efficient approach to solve quadratic programming problems subject to equality constraints via Theory of Connections (ToC). This is done without using the traditional approach of using Lagrange multipliers and the solution is

provided in a closed-form. Two distinct constrained expressions, always satisfying the equality constraints, are introduced. The unknown vector to optimize is then the free vector, g, introduced by the ToC in the constrained expressions. The solution to nonlinear programming is obtained by nonlinear Newton iterations, starting from an initial vector, g0, estimated by approximating the nonlinear objective function to the second order.

11:00 AAS 19-915 Revisiting "How Many Impulses?" Question

Ehsan Taheri, Auburn University; John L. Junkins, Texas A&M University

Edelbaum asked a fundamental question in a 1967 paper: "How Many Impulses?" The question asks: For a general orbit transfer with some unknown number, N_{imp} of impulsive velocity changes: 1) how many impulses, 2) at what times, and 3) in what direction should these impulses be applied to minimize the total impulse, Δv? Impulsive solutions determine bounds on both minimum time and minimum fuel extremals and also provide reachability insights. We present a unified approach that encompasses all extremal impulsive and low-thrust trajectories by taking a reverse approach, which presents a systematic approach to answer Edelbaum's question.

11:20 AAS 19-904 FAST SOLUTION OF OPTIMAL CONTROL PROBLEMS WITH L1 COST

Simon Le Cleac'h, Stanford Unversity; Zachary Manchester, Stanford University

We propose a fast algorithm for solving optimal control problems with L1 control cost. Convergence to global optimum is guaranteed for systems with linear dynamics, and the algorithm can also be used to find local optima for non-linear dynamical systems. Our approach relies on the alternating direction method of multipliers (ADMM) and uses a fast trajectory optimization solver based on differential dynamic programming (DDP). The low computational complexity coupled with the fast execution of this algorithm make it suitable for implementation in flight software.

Aug 12, 2019 Longfellow

Session 2: Earth Orbital & Planetary Missions

Chair: Kyle T. Alfriend, Texas A&M University

8:00 **AAS 19-742** **Optimal Deorbit from Low Earth Orbit with Electric Propulsion**

Nathan Parrish, Advanced Space, LLC; Jeff Parker, Advanced Space, LLC; Cameron Meek, OneWeb; Aurelie Heritier, OneWeb

As more and more spacecraft use the low Earth orbit (LEO) regime, it is critical that all players act responsibly and deorbit at end-of-life. Here, we analyze approaches to minimize the time to deorbit. Key parameters are identified and described, considering constraints on fuel budget and thrust limitations from eclipses. A simple and effective general strategy for deorbit is identified. The OneWeb internet constellation is used as an example for finding the optimal parameters. The objective of the deorbit strategy is to ensure safety for every vehicle in nearby orbits, while deorbiting quickly within propellant and operational constraints.

8:20 **AAS 19-748** **Mission Opportunities to Trans-Neptunian Objects - Part VI**

Daniel Johnson, University of Tennessee; Zackery Crum, Univetsity of Tennessee; Garrett Mitchell, The University of Tennessee; Samuel Walters, University of Tennessee; Adam Dalton, University of Tennessee; Brandon Davis, University of Tennessee; Benjamin Dolmovich, University of Tennessee; Meghan Green, University of Tennessee; Amanda Williams, University of Tennessee; Gerald Wise, University of Tennessee; James Evans Lyne, University of Tennessee

The distant region of the Solar System known as the Kuiper Belt extends outward from Neptune and contains thousands of objects, only a small percent of which have been catalogued to date. New Horizons is the only mission that has specifically targeted objects in this area. The present study describes mission opportunities to Kuiper Belt objects using low C3 Earth departures, enabled by the use of delta V-Earth gravity assist maneuvers. This approach allows for much larger probes or the possibility of multiple probes departing on a single launch vehicle.

8:40 **AAS 19-649** **Optical Methods for Finding New Natural Satellites of the Solar System's Outer Planets**

Paul McKee, Rensselaer Polytechnic Institute; William Parker, Rensselaer Polytechnic Institute; John Christian, Rensselaer Polytechnic Institute

The distribution of orbits of the natural satellites (moons) around the outer planets offers important clues about the dynamical history of our Solar System. It is necessary, therefore, that we construct image acquisition strategies and data processing techniques that allow us to find new moons in a systematic way. There are advantages to searching for very small moons with a spacecraft operating in the vicinity of the planet. In this work, we present an image processing technique based on the Radon Transform that can automatically find unknown (new) moons in a sequence of images collected by an exploration spacecraft.

9:00 AAS 19-796 Overview of the Deep Space Atomic Clock Technology Demonstration Mission

Todd Ely, Jet Propulsion Laboratory; Jill Seubert, NASA / Caltech JPL

The Deep Space Atomic Clock (DSAC), a NASA Technology Demonstration Mission (TDM), is scheduled for launch no earlier than late-Spring 2019. The mission plan is to conduct a yearlong demonstration of a mercury ion ($^{199}Hg^{+}$) atomic clock to characterize its space-based performance and to validate its utility for deep space navigation and radio science. This work will briefly review the DSAC technology and its benefits for deep space navigation and science then describe the DSAC mission's operational concepts, methods, and, finally, anticipated results.

9:20 AAS 19-613 Impulsive Least-Squares Orbit Maintenance using Gauss's Variational Equations

Daniele Mortari, Texas A&M University; Gang Zhang, Harbin Institute of Technology

Based on the Gauss's variational equations (GVEs), the least-squares method is studied for impulsive orbital-element corrections in orbit transfer problems. Both single impulse and multiple impulses are considered for the first-order and second-order GVEs. For the single impulse, a nonlinear least-squares iteration method for the minimum orbit error is provided to simultaneously solve impulse vector and impulse position. For the multiple impulses, a least-squares method for the minimum impulse cost is proposed to solve the two-impulse and three-impulse corrections for the out-of-plane and in-plane orbital elements, respectively; both the impulse positions and impulse vectors are analytically derived.

9:40 AAS 19-802 OPTIMIZATION OF LOW THRUST TRANSFER ORBITS OF A SPACECRAFT CONSIDERING THE RADIATION HAZARD FROM THE VAN ALLEN BELTS

Rodrigo Schmitt, Institute of Astronomy, Geophysics and Atmospheric Sciences of University of Sao Paulo; Gerson Barbosa, INPE; Antonio Fernando Bertachini Prado, INPE

A spacecraft transfer from a low Earth orbit to outside the Earth sphere of influence using solar electric propulsion is considered. The spacecraft crosses the Van Allen belts many times during the transfer, which can damage the onboard electronic equipment. The belt was modeled using discrete regions with given proton and electron fluxes and used to compute the radiation dose absorbed by the spacecraft for various transfer orbits. The final mass of the spacecraft is calculated for each transfer as well, in order to minimize fuel consumption. This estimate is done for various parking orbits and transfer times.

10:00 Morning Break

10:20 AAS 19-753 Extended Phase Space Realization for Attitude Dynamics of an Axisymmetric Body in Eccentric Orbit

Roshan Thomas Eapen, Texas A&M University; Kyle T. Alfriend, Texas A&M University; Manoranjan Majji, Texas A&M University, College Station

This paper investigates the attitude dynamics of a rigid fast-rotating axisymmetric body in an eccentric orbit using a Hamiltonian formulation in the Serret-Andoyer variables. The Hamiltonian is formulated using the extended phase space wherein the true anomaly, which arises due to the Keplerian nature of the orbit, is treated as a coordinate along with a dummy momenta associated with it. Numerical checks verify that the Hamiltonian formulated captures all the information of the attitude motion. The gravity-gradient potential is modeled as a perturbation for averaging using Lie-series method and an averaged Hamiltonian up to fourth order is obtained.

10:40 AAS 19-657 Solar Radiation Pressure Effects on the orbital motion at SEL2 for the James Webb Space Telescope

Ariadna Farres, University of Maryland Baltimore County; Jeremy Petersen, a.i. solutions; Karen Richon, NASA GSFC

The James Webb Space Telescope (JWST) will orbit around the Sun-Earth L2 (SEL2) Libration Point. Due to JWST’s large sunshield, which is always facing the Sun to protect the telescope’s instruments, Solar Radiation Pressure (SRP) has an important effect on JWST‘s orbital motion around SEL2. Moreover, SRP is highly dependent on the telescope’s attitude with respect to the Sun-telescope line. This paper explores the impact of SRP for different attitude profiles on the shape and size of Libration Point Orbits at SEL2.

11:00 **AAS 19-903** **Stable Low Altitude Lunar Periodic Orbits using the GRAIL Gravity Field**
Sean McArdle, University of Texas at Austin; Ryan Russell, The University of Texas at Austin

As an update to a study that predated the GRAIL mission, families of very low altitude lunar periodic orbits are revisited using a modern high fidelity gravity field. The periodic orbits, computed with a new multiple shooting second order trust region method, are mapped in detail across the inclination and altitude design space. Geometry and stability are examined in the context of potential scientific and exploration applications. These solutions, now accurately accounting for far side gravity features, represent an improvement in our ability to predict long term stable lunar orbits.

11:20 **AAS 19-860** **Vehicle and Mission Design Options for Very Low Earth Orbit CubeSats**
James Williams, University of Illinois at Urbana-Champaign; Michael Gray, University of Illinois at Urbana-Champaign; Zachary Putnam, University of Illinois at Urbana-Champaign

Investigations into very low Earth Orbit (VLEO) have become much more available with the increasing popularity of smallsat missions. Current analysis tools treat the aerodynamic effects related to these orbits in a decoupled manner: Deorbit analyses are focused exclusively on aerodynamic drag, while stability analyses are focused on aerodynamic torque. Analysis which couples these effects are able to provide more holistic results. This work intends to compare various control system and vehicle design criteria to determine favorable options for vehicles intending to operate in this regime.

Aug 12, 2019 Hawthorne

Guidance, Navigation & Control II

Chair: Peter Lai, NASA Jet Propulsion Laboratory

13:30 AAS 19-801 SUN-AVOIDANCE SLEW PLANNING ALGORITHM WITH POINTING AND ACTUATOR CONSTRAINTS

Mohammad A. Ayoubi, Santa Clara University; Junette Hsin, Maxar Space Solutions

This paper presents a geometric approach for a sun (or any bright object) avoidance slew maneuver with pointing and actuator constraints. We assume spacecraft has a single light-sensitive payload with control-torque and reaction wheels' angular momentum constraints. Furthermore, we assume the initial and final attitudes, instrument boresight vector, and sun vector are known. Then we use Pontryagin's minimum principle (PMP) and derive the desired or target-frame quaternions, angular velocity and acceleration. In the end, a Monte Carlo simulation is performed to show the viability of the proposed algorithm with control-torque and angular momentum constraints.

13:50 AAS 19-726 CHANGO: A Software Tool for Boost Stage Guidance of the Space Launch System Exploration Mission 1

Matthew Hawkins, Jacobs Space Exploration Group; Naeem Ahmad, NASA MSFC; Paul von der Porten, NASA Marshall Space Flight Center

The Space Launch System (SLS) Exploration Mission 1 (EM-1) test flight will use open-loop guidance for Boost Stage (BS) flight. A table of attitude commands as a function of altitude, called the chi table, will be loaded onto the flight computers. The chi table will be generated using the measured winds on launch day by the Chi Angle Optimizer (CHANGO) software tool. Details of CHANGO’s design are given, including a 3 Degrees of Freedom (3-DOF) simulation and a numerical minimization routine. CHANGO’s use in launch day operations is also described.

14:10 AAS 19-718 Fuel-efficient Powered Descent Guidance on Planetary Bodies via Theory of Connection

Enrico Schiassi, University of Arizona; Roberto Furfaro, The University of Arizona; Hunter Johnston, Texas A&M University; Daniele Mortari, Texas A&M University

14:30 AAS 19-739 Error Analysis of Closed-loop Attitude Estimation and Control System for Spacecraft High Accuracy Pointing

Divya Bhatia, Institute of Flight Guidance, Technical University of Braunschweig

Error analysis is indispensable specifically for missions requiring stringent system performances. In this paper linear covariance techniques are employed for closed-loop Attitude Determination and Control System (ADCS) error analysis of one such mission with sub-arcsec pointing requirement named ‘InfraRed Astronomy Satellite Swarm Interferometry (IRASSI)’. Covariance analysis employ an augmented state formulation to determine the variances of the true and expected attitude estimation errors, variances of true pointing errors of the closed-loop system and variance of the required control effort. The implementation substantiates the claim that linear covariance analysis is a very useful tool for fast analysis of closed-loop ADCS.

14:50 AAS 19-881 Onboard Optical Navigation for Asteroid Explorer by Asteroid Shape Model

Shuya Kashioka, SOKENDAI; Yuichi Tsuda, Japan Aerospace Exploration Agency; Yuki Takao, The University of Tokyo; Takatoshi Iyota, Soka University; Genki Ohira, SOKENDAI

We present the onboard navigation system for the approaching and landing on an asteroid in deep space. The focus of this research is to apply a heuristic optical navigation method used in Hayabusa2 called GCP-NAV into an on-board processable algorithm. We developed the above algorithm and applied to Hayabusa2 flight data of touchdown operation in computer and hardware simulation. The estimation result that fits the error of up to 1 pixel on the image coordinates was obtained and the calculation time was decreased below 1/10 compared with calculation time on CPU.

15:10 AAS 19-919 Control and Simulation of a Deployable Entry Vehicle with Aerodynamic Control Surfaces

Benjamin Margolis, NASA

In this paper, we present the design of a control system to follow angle-of-attack and sideslip guidance commands for the Lifting Nano-ADEPT deployable entry vehicle. The control design is based on linear quadratic regulator optimal control techniques. We show through simulation that the controller is able to accurately track guidance commands within the vast operating regime for entry.

15:30 Afternoon Break

15:50 **AAS 19-868** **Variational Lambert Problem with uncertain dynamics**

Paolo Panicucci; Jay McMahon, University of Colorado Boulder; Michel Delpech, CNES; Emmanuel Zenou, ISAE-SUPAERO

In the presented paper the variational Lambert problem with stochastic dynamics is presented and analyzed. The importance of this problem is mainly due to the necessity to navigate the spacecraft in a completely or partially unknown dynamical environment. Applications of this problem are multiple: on-board orbit determination by considering maneuver estimation, guidance maneuver correction or uncertainty quantification of future maneuver. In the present research the stochastic Lambert's problem and its linearized formulation are investigated. Validation results and an operational scenario are shown and commented.

16:10 **AAS 19-804** **Analytical State Transition Matrix For Dual-Quaternions For Spacecraft Pose Estimation**

Andrew Goodyear, Penn State University; Puneet Singla, Pennsylvania State University; David B. Spencer, Pennsylvania State University

An analytical expression for a state transition matrix (STM) is preferable to numerical integration of the STM for real-time estimation of spacecraft pose. With a discrete STM for a dual quaternion state vector, the dual quaternion error covariance can be propagated analytically between two measurement time intervals. This work provides analytic solutions for a dual quaternion STM, dual quaternion error STM, and discrete process noise covariance matrices. These state transition matrices are utilized to compute innovation terms in the update part of the EKF. Numerical simulations are performed to validate the EKF development for different measurement models.

16:30 **AAS 19-916** **Collision Avoidance Around Small Bodies Using Low-Thrust Guidance**

Donald Kuettel, Colorado Center for Astrodynamics Research; Jay McMahon, University of Colorado Boulder

A recent discovery from NASA's OSIRIS-REx mission confirmed particle plumes erupting from the surface of asteroid Bennu. While exciting, this discovery has many implications for small body missions around similar rubble-pile asteroids. One question that needs to be answered is how to ensure that spacecraft in orbit around active rubble-pile asteroids do not collide with any of these ejected particles? Following previous work, this paper develops autonomous, low-thrust guidance algorithms used to actively avoid spacecraft collisions with ejected particles under uncertainty. More specifically, this paper examines several different continuous guidance algorithms to quantify each algorithm's collision avoidance performance in the small body

16:50 AAS 19-650 SUN SEARCH DESIGN FOR THE PSYCHE SPACECRAFT

Daniel Cervantes, NASA Jet Propulsion Laboratory; Peter Lai, NASA Jet Propulsion Laborary; Alex Manka, NASA Jet Propulsion Laboratory; Aditi Ratnaparkhi, Maxar Space Solutions; Eric Turner, SSL MDA

Psyche is a scientific mission to explore the large asteroid (16) Psyche that orbits the Sun at ~3 AU. Managed by JPL, it is the first instance of SSL's product line of geosynchronous communication satellites being repurposed for deep space. This paper presents the design of a unique sun sensor configuration for Safe Mode of the spacecraft. It enables quick, robust, and propellant-efficient safing while leveraging sensors, avionics, and algorithms that have extensive, flight-proven heritages.

17:10 AAS 19-655 The Evolution of Deep Space Navigation: 2009-2012

Lincoln Wood, Jet Propulsion Laboratory, Caltech

The exploration of the planets of the solar system using robotic vehicles has been underway since the early 1960s. During this time the navigational capabilities employed have increased greatly in accuracy, as required by scientific objectives and enabled by technological improvements. This paper is the sixth in a chronological sequence dealing with the evolution of deep space navigation and covers the time interval 2009 to 2012. The paper focuses on the observational techniques that have been used to obtain navigational information, propellant-efficient means for modifying spacecraft trajectories, and the computational methods that have been employed, tracing their evolution through 12 missions.

Aug 12, 2019 Longfellow

Orbital Dynamics, Perturbations, and Stability

Chair: Roby Wilson, Jet Propulsion Laboratory

13:30 **AAS 19-731** **Approximate Analytic Representations For Fixed-angle Low-thrust Trajectories**

Guanwei He, Pennsylvania State University; Robert Melton, Pennsylvania State University

This paper presents an approximate solution to the equations of a spacecraft moving under the constant, fixed-angle, low-level thrust, and influenced by an inverse-square gravitational field, deriving by using the linear perturbation method. The approximate solution is compared with direct numerical integration, and shows a relatively low errors and noticeable improvement in calculation speed.

13:50 **AAS 19-684** **Analytic Approximations of Orbit Geometry in a Rotating Higher Order Gravity Field**

Ethan Burnett, University of Colorado Boulder; Hanspeter Schaub, University of Colorado

This paper introduces new analytic approximations of the orbital state for a subset of orbits in a rotating potential with gravitational harmonics C20 = −J2 and C22. The approximations are fully developed for near-circular orbits with initial mean motion n0 around a body with rotation rate c. The approximations are shown to be valid for values of Γ = c/n0 > 1, with accuracy decreasing as Γ → 1, and singularities at Γ = 1. The methodology in this paper can be adapted to approximate eccentric orbits in more general potentials, and the necessary modifications are discussed.

14:10 **AAS 19-736** **Orbit Propagation via the Theory of Connections**

Hunter Johnston, Texas A&M University; Daniele Mortari, Texas A&M University

This paper presents a new method for perturbed orbit propagation based on the Theory of Connections. This method uses the analytical solution for the unperturbed two-body problem as a baseline, and searches for the term to add to the baseline that will capture all of the perturbations. In order to validate the method, an unperturbed two-body problem is solved with a poor initial orbit guess and the solution accuracy is quantified by determining the evolution of constant orbital parameters. The next step is to validate this method by applying perturbations and compare the solution produced with a high accuracy integrator.

14:30 AAS 19-780 Quasi-Heliosynchronous Orbits

Maria Lívia da Costa, National Institute For Space Research; Rodolpho Moraes, UNIFESP; Antonio Fernando Bertachini Prado, INPE; Jean Paulo S. Carvalho, UNIFESP - Instituto de Ciéncia e Tecnologia

In order to solve correctly the hard task of searching for heliosynchronous orbits when the equations of motion become coupled due to the inclusion of other terms in the disturbing potential, the concept of quasi-heliosynchronous orbits is introduced. Through the tools of the non-linear optimization, quasi-heliosynchronous orbits are found for artificial satellites around the following bodies: Moon, the Gallilean satellites and Titan. In addition, the quasi-critical inclinations are revised under the same optimization point of view.

14:50 AAS 19-601 Long-Term Numerical Propagation for Earth Orbiting Satellites

David A. Vallado, Analytical Graphics, Inc.

Numerical propagation techniques have been extensively studied and are routine for precise satellite operations. Most studies focus on time spans of a few days to a week, specific orbital classes, or interplanetary orbits. As numerical operations replace older analytical techniques, it's useful to quantify accuracy performance for propagations of several months, to years. This paper performs long-term numerical propagation comparisons against reference orbits in a variety of orbital classes. Semianalytical techniques are also used in the comparisons including a general discussion of finding the initial osculating to mean conversion. Finally, orbital size, shape, and orientation considerations are examined.

15:10 AAS 19-914 Lunisolar Perturbations of High-Eccentricity Orbits Such as the Magnetospheric Multiscale Mission

Trevor Williams, NASA/Goddard Space Flight Center; Eric Palmer, a.i. solutions, Inc.; Dominic Godine, ai Solutions, Inc.; Neil Ottenstein, a.i. solutions, Inc.; Rich Burns, NASA; Jacob Hollister, ai Solutions, Inc.

For highly eccentric orbits such as that of the Magnetospheric Multiscale (MMS) mission, with apogee radius now 29.34 Earth radii, the third-body effects of Sun and Moon are the major perturbations. One key consequence is an oscillation in MMS perigee altitude, on an approximately 6 year cycle. This variation has already required perigee-raise maneuvers to avoid an untimely reentry. There is also a long-term evolution in the orientation of the MMS orbit, with period roughly twice as long. This effect may potentially be useful for MMS science studies, as it can bring the spacecraft into new regions of the magnetosphere.

15:30 Afternoon Break

15:50 AAS 19-624 Computing Kepler Equations for Analytic Orbit Propagation

Gim Der, DerAstrodynamics

This paper presents an innovative technique to compute 2-Body and perturbed Kepler equations accurately and robustly for analytic orbit propagation even with eccentricity of 0.99999. The traditional Vinti algorithm that includes J2, J3 and most of J4 is extended to include Sun and Moon perturbations for deep space objects especially those in GEO. This efficient Vinti algorithm is applied to solve the computational intensive correlation problem between radar/optical detection data and cataloged objects. A Vinti state vector prediction between GPS locks for GPS equipped Cubesats is being flight tested in the GPSRM 1 Cubesats of Proxima I & II.

16:10 AAS 19-644 Navigation Models for Psyche Electric Propulsion Uncertainty

Nicholas Bradley, CalTech / Jet Propulsion Laboratory; Steve Snyder, CalTech / Jet Propulsion Laboratory; Drew Jones, Jet Propulsion Laboratory, Caltech; Denis Trofimov, CalTech / Jet Propulsion Laboratory; Dayung Koh, JPL

The Psyche mission will launch to the main belt asteroid (16) Psyche in August 2022, using four Hall Effect Thrusters as the sole method of deterministic thrusting. Hall Effect thrusters have never flown in deep-space, and their performance uncertainty must be accounted for to assess expected navigation accuracy for the mission. We first discuss existing data on which our models are based. Then, we present the evolution of the navigation uncertainty model for low-thrust, with correlated stochastic and bias parameters. We explore trajectory uncertainty sensitivity to low-thrust uncertainty model parameters. Finally, results of expected navigation performance are presented.

16:30 AAS 19-805 APPLICATION OF UDWADIA-KALABA FORMULATION TO THREE-BODY PROBLEM

Harshkumar Patel, Embry-Riddle Aeronautical University; Troy Henderson, Embry-Riddle Aeronautical University; Morad Nazari, Embry-Riddle Aeronautical University

This paper introduces the Udwadia-Kalaba formulation of constrained dynamics to the three-body problem (Sun-Earth-Spacecraft). A dynamic model of the three-body system is presented to analyze the unconstrained motion of spacecraft at the Lagrange point L1. The results verify the instability of L1 due to perturbation from the solar radiation pressure (SRP). Then, the Udwadia-Kalaba formulation is applied to derive the equation of motion of spacecraft with additional constraints to the three-body systems. The results provide thrust force required for spacecraft to recover its position to the L1 from the perturbation of SRP.

16:50 **AAS 19-642** **Long-term Survey of LAMR and HAMR Objects Using Analytic Techniques**

Smriti Nandan Paul, Purdue University; Carolin Frueh, Purdue University

Orbital evolution can be achieved through numerical techniques but they are expensive. Propagation using analytic techniques is a convenient alternative. It cannot be assumed that initial orbital conditions are error-free. This paper uses analytic techniques to analyze the evolution of uncertainties in orbital trajectories due to uncertainties in initial state and design parameters. The uncertainty analysis will be carried out in presence of Earth gravity, third-body gravities, and solar radiation pressure. Unscented transformation based sigma points is used for propagation of initial uncertainties. As an application, this paper will study low and high area-to-mass ratio objects in sensor tasking scenario.

Aug 12, 2019 Rines A

Relative Motion, Formation Flying, Rendezvous and Proximity Operations II

Chair: Jeffrey Stuart, Jet Propulsion Laboratory

13:30 AAS 19-648 Constellation Planning Methods for Sequential Spacecraft Rendezvous Using Multi-Agent Scheduling

Skylar Cox, Space Dynamics Laboratory; Nathan Stastny, Space Dynamics Laboratory; Greg Droge, Utah State University; David Geller, Utah State University

This paper addresses the RPO constellation assignment problem by developing a responsive utility function for tasking a constellation of LEO satellites to a number of spacecraft servicing tasks. The paper develops the utility function that considers both value of servicing RSO spacecraft in conjunction with the associated delta-V and time costs. A highly-capable and operationally-relevant task allocation method, called the consensus-based bundle algorithm (CBBA), is leveraged for both task specification as well as distributed assignment. It is demonstrated that this methodology provides a robust technique for RPO constellation management.

13:50 AAS 19-679 Geometric Formations Using Relative Orbital Elements and Artificial Potential Functions

Sylvain Renevey, Purdue University; David A. Spencer, Purdue University

In this paper, geometric relative orbit formations are established using a control algorithm based on relative orbital elements and artificial potential functions. Numerical simulations are presented to illustrate the effectiveness of the control algorithm. The first case study is that of a triangular lattice composed of nine spacecraft distributed onto two circular relative orbits. Then, the design and establishment of a thirty-seven spacecraft formation composed of two hexagonal lattices is presented. Finally, the algorithm is extended to a different set of relative orbital elements and is illustrated with the design of a helix trajectory for on-orbit inspection.

14:10 AAS 19-941 Launch, Transport, Aggregation, and Assembly of an In-Space Assembled Telescope

Bo Naasz, NASA

In-space assembly of a large space telescope uses launch, transport, aggregation, and assembly of several launch-vehicle-loads of cargo to construct a large (e.g. 10-20m diameter) primary mirror observatory. Such an observatory would be capable of advanced astrophysical observations

including direct spectroscopy of extra-solar planets. Observatory cargo will be delivered as unpressurized cargo to the assembly point, where resident robotics will capture the cargo delivery vehicle, and remove and install the cargo onto the growing observatory. We present a preliminary concept of operations for launch, aggregation, and assembly, and a parametric cost and assembly time study, based on work performed during NASA Science Mission Directorate's In-Space Assembled Telescope (ISAT) study.

14:30 AAS 19-662 Constrained Energy-Optimal Guidance in Relative Motion via Theory of Functional Connections and Rapidly-Explored Random Trees

Kristofer Drozd, University of Arizona; Roberto Furfaro, The University of Arizona; Daniele Mortari, Texas A&M University

In this paper, we present a new approach to solving constrained energy-optimal guidance problems for spacecraft relative motion. The proposed methodology is developed on two fundamental blocks, i.e. solution of boundary-value problems via Theory of Connections (ToC) and generation of dynamically feasible opti-mal trajectory via Rapidly-explored Random Trees (RRT*). The method enables fast generation of trajectories in relative motion that drive the chaser spacecraft to the target in an energy-optimal fashion while satisfying state constraints aris-ing from operational constraints.

14:50 AAS 19-832 Analytic Center of Illumination solutions to aid Relative Navigation with Partially Resolved Imagery

Kevin Kobylka, Rensselaer Polytechnic Institute; John Christian, Rensselaer Polytechnic Institute; Jacob Puritz, Rensselaer Polytechnic Institute

The distance between a pair of spacecraft executing a rendezvous changes by many orders of magnitude during their on-orbit encounter. If optical sensors are to be used for relative navigation in such a scenario, it is reasonable to assume that the observed spacecraft will transition from an unresolved object (at long range), to a partially resolved object (at intermediate range), to a fully resolved object (at close range). This work seeks to enhance techniques within the partially resolved regime by developing analytical solutions to relate the center of illumination to their geometric center for a number of common geometric primitives.

15:10 AAS 19-850 Autonomous Characterization of an Asteroid from a Hovering Trajectory

Shota Takahashi, University of Colorado Boulder; Daniel Scheeres, University of Colorado Boulder

Asteroid exploration missions must deal with large uncertainties in a target body's gravity and shape upon rendezvous. Parameters associated with the asteroid are typically estimated after arrival through costly ground-based observations. In this paper, we consider autonomous operation of a spacecraft as a solution to reduce the cost. We focus on the period between the interplanetary and close hovering phase. The spacecraft needs to localize itself, estimate the asteroid's model parameters, and travel to a predefined hovering state. Solution methods based on Partially Observable Markov Decision Process (POMDP) will be applied to solve the problem.

15:30 Afternoon Break

15:50 AAS 19-713 Morse-Lyapunov-Based Decentralized Consensus Control of Rigid Body Spacecraft in Orbital Relative Motion

Eric Butcher, University of Arizona; Mohammad Maadani, University of Arizona

An algorithm is proposed for almost globally asymptotically stable consensus control of multi-agent rigid body spacecraft in orbital relative motion using Morse-Lyapunov analysis in the framework of SE(3). The control objective is to stabilize the relative pose configurations with velocity synchronization of the spacecraft which share their states according to a static communication topology in the presence of gravitational forces and torques. The feedback control design is conducted on the dynamic level where mass and inertia may be large and thus the strategy is applicable to quickly maneuvering and tumbling rigid spacecraft, and a potential-based collision avoidance scheme is also implemented.

16:10 AAS 19-706 Nonlinear Optimal Tracking Control of Two-Craft Coulomb Formation in Elliptic Chief Orbits

Muhammad Wasif Memon, Embry-Riddle Aeronautical University; Morad Nazari, Embry-Riddle Aeronautical University; Richard Prazenica, Embry-Riddle Aeronautical University ; Dongeun Seo, Embry-Riddle Aeronautical University

Coulomb formation of two spacecraft is considered in elliptic orbits. The uncontrolled relative dynamics of the formation are unstable. Hence, a charge and thruster nonlinear optimal tracking feedback control is designed to stabilize and maintain a constant relative distance between the spacecraft along the nadir direction in the Hill frame. To indicate the significance of using Coulomb effects in terms of fuel costs, the integrated control effort of the thrusters is studied and compared to the case when the Coulomb effects are not taken into account.

16:30 AAS 19-627 HelioSwarm: Space-Based Relative Ranging for a Cubesat Cluster Mission in a 2:1 Lunar Resonant Orbit

Lisa Policastri, Space Exploration Engineering (SEE); James Woodburn, Analytical Graphics, Inc.

The HelioSwarm mission concept consists of a cluster design with 1 Hub and 10 Nodes co-orbiting the Earth in a 2:1 Lunar resonant orbit. A variety of navigation constraints, assumptions, and schedules were considered during navigation strategy design to minimize the need for ground-based tracking and communication. Each Node will only be capable of communicating with the Hub, with no direct connections to other Nodes or the ground. The Hub will be tracked from the ground and perform two-way inter-satellite ranging with each Node. Simulated ground and space-based tracking are used for the determination of expected orbit accuracy.

Aug 12, 2019 Eastland Ball Room

Trajectory Design & Optimization II

Chair: Pradipto Ghosh, Analytical Graphics, Inc.

13:30 AAS 19-838 Robust Trajectory Optimization Using Minimum-Error Cost Functions

Erica Jenson, University of Colorado Boulder; Daniel Scheeres, University of Colorado Boulder

An innovative approach to robust trajectory optimization in which state error statistics are minimized directly will be applied to orbit transfers in the two-body problem. Both initial state error and multiplicative control noise will be considered. The second raw moment of the state error about a nominal trajectory will be used to form a Bolza-type, minimum-error cost function, for which optimal trajectories will be found using indirect multiple-shooting methods. Minimum-error optimization will be demonstrated for orbit transfers in the low-gravity environments around asteroids, where fuel requirements are small but uncertainties are large. Robustness will be verified through Monte Carlo simulations.

13:50 AAS 19-763 A Convex Optimization Approach for Finite-Thrust Time-Constrained Cooperative Rendezvous

Boris Benedikter, Sapienza University of Rome; Alessandro Zavoli; Guido Colasurdo, Università di Roma Sapienza

This paper presents a convex programming approach to the optimization of a cooperative rendezvous, that is, the problem of two distant spacecraft that simultaneously operate to get closer. Since it cannot be readily solved as a convex optimization problem, a combination of lossless and successive convexification techniques is adopted to generate a sequence of convex subproblems having the same solution as the original one. Convergence towards the optimal solution is guaranteed in a limited, short, time by using highly efficient numerical algorithms. Numerical results for several cases are presented and compared with those provided by an indirect method.

14:10 AAS 19-690 Launch Opportunity Analysis of GEO Transfer with High Inclination using Lunar Gravity Assist

Su-JIN Choi, Korea Aerospace Research Institute; John Carrico, Space Exploration Engineering, LLC; Michel Loucks, Space Exploration Engineering (SEE); Hoonhee Lee, Korea Aerospace Research Institute; Se-Jin Kwon, Korea Advanced Institute of Science and Technology

Naro Space Center located in the middle latitude(around 34 degrees) of north hemisphere is constructed to test KSLV-II and to mainly launch SSO satellite. Initial Inclination after launch separation reaches 80 degrees for lunar orbiter. For GEO mission, initial inclination directly affects the plane change maneuver. In order to launch GEO mission from Naro Space Center, GEO transfer using LGA is considered. However, when it should be launched can be an important issue because the Moon has a small eccentricity so the distance between the Earth and the Moon is varying. This study will show the overall trajectory and converged values.

14:30 AAS 19-932 **Design and Synthesis of Entry, Powered Descent and Landing Maneuver Trajectories using Motion Envelopes**
Melissa Onishi, University of Hawaii at Mānoa

Previous work dedicated to this area of study describe the results of MATLAB simulations which focused on the formulation of manifolds of the initial and final points for powered descent and landing. These manifolds can be generated by a construction of envelopes of the landing trajectories using a vast range of terminal conditions for the trajectory and lander's parameters. This paper also discusses improvements to the current design of three primary events throughout the Entry, Descent and Landing (EDL) maneuver. A 2-D analysis along the x and z plane revealed that it is possible to construct each phase individually.

14:50 AAS 19-768 **Dependent Variable Integration for event finding with validation in orbit propagation**
Anthony Iannuzzi, U.S. Naval Research Laboratory

Space mission planning may rely on orbital and system level events to trigger a desired response. These events are zero-crossings of mathematical functions. Alternative to using a root-finder, Henon's Method integrates to the event in a single step; however, it is not applicable in most astrodynamics applications. A new category of event finders, Integrate To Solve (ITS), and a new Derivative-Free Option (DFO) is introduced. ITS methods include Henon's Method and two new methods. These new methods and DFO extend applicability. Ground station access events are used to evaluate the performance of the new ITS methods with and without DFO.

15:10 AAS 19-770 **ACCURATE LOW-THRUST ORBIT TRANSFER SOLUTIONS IN EQUINOCTIAL ELEMENTS USING AN ANALYTIC REPRESENTATION OF THE GEOPOTENTIAL**
Zachary Folcik, MIT Lincoln Laboratory; Paul J. Cefola, University at Buffalo (SUNY)

Analytical gravity models are included in the equinoctial element formulation of the low-thrust optimal equations of motion and the adjoint equations for the Lagrange multipliers. Geopotential models of up to degree and order four are developed and tested in this paper; the capability to write analytic expressions for arbitrary degree and order geopotentials follows from the Maxima symbolic algebra approach employed. Previous work using tensors to transform accelerations from inertial coordinates to Euler-Hill coordinates is extended for a general geopotential. The correctness of the tensors is verified. Optimal low-thrust orbital transfer solutions under the influence of gravitational perturbations are described.

15:30 Afternoon Break

15:50 AAS 19-719 Copernicus 5.0: Latest Advances in JSC's Spacecraft Trajectory Optimization and Design System

Jacob Williams, NASA Johnson Space Center; Anubhav Kamath, MRI Technologies; Randy Eckman, NASA Johnson Space Center; Gerald Condon, NASA; Ravishankar Mathur, Emergent Space Technologies, Inc.; Diane Davis, a.i. solutions, Inc.

This paper describes the latest upgrades that have been made to JSC's Copernicus trajectory optimization program for the upcoming 5.0 release. Copernicus has undergone significant refactoring in recent years in order to make the tool more powerful, versatile, and user-friendly. The 5.0 release includes a new Python-based GUI and scripting interface, new 3D graphics upgrades, and a host of architectural modifications. The paper will discuss the implementation of the new architecture and its capabilities. Examples will be shown using some of the new features as applied to different trajectory problems.

16:10 AAS 19-789 Parker Solar Probe Mission Design

Yanping Guo, JHUAPL

A mission to the sun, called Solar Probe, was first considered in 1958 and stayed in concept and feasibility studies for five decades until 2007 when a new mission design was created that changed the original mission architecture. The re-designed mission was named Solar Probe Plus, due to significant advantages in technical implementation and science return, until 2017 when it was renamed Parker Solar Probe (PSP). This paper presents an overview of mission design changes and the final PSP mission design before it was launched on August 12, 2018, including launch and detailed mission trajectory.

16:30 AAS 19-661 High-Fidelity Multiple-Flyby Trajectory Optimization Using Multiple-Shooting

Donald Ellison, NASA Goddard Space Flight Center; Jacob Englander, NASA Goddard Space Flight Center

Rendering a complex spacecraft trajectory in high-fidelity can be an expensive endeavor, both computationally and from a time/cost standpoint. It is important to have an efficient process for converting a trajectory from an inexpensive lower-fidelity model to high-fidelity. We present a method for computing high-fidelity trajectories that relies on multiple shooting, nonlinear programming and numerical integration. The solution method allows for the rapid conversion of lower-fidelity trajectories to high-fidelity. The procedure converts any zero-radius sphere of influence gravity-assist events to fully integrated flyby events. Several numerical examples are presented that showcase the flexibility of the high-fidelity rendering process across multiple mission types and flight regimes.

Aug 13, 2019 Longfellow

Dynamical Systems Theory I

Chair: Natasha Bosanac, University of Colorado, Boulder

8:00 **AAS 19-696** **High-Energy Lunar Capture via Low-Thrust Dynamical Structures**

Andrew Cox, Purdue University; Kathleen C. Howell, Purdue University; David Folta, NASA Goddard Space Flight Center

Current and future spacecraft will leverage low-thrust propulsion to navigate from high-energy transfer trajectories to low-energy orbits near the Moon. Due to the long burn durations required for such energy changes, identifying suitable low-thrust arcs remains a design challenge. Periapse maps are employed to explore the dynamics of low-thrust, energy-optimal arcs in the lunar vicinity. Dynamical structures that separate transit and captured motion on these maps are identified and leveraged to construct preliminary low-thrust trajectory designs, with additional insights available from a combined low-thrust, multi-body model.

8:20 **AAS 19-769** **Linking Low- to High-Energy Dynamics of Invariant Manifold Tubes, Transit Orbits, and Singular Collision Orbits**

Kenta Oshima, National Astronomical Observatory of Japan

This study aims to link low- to high-energy transport dynamics in the planar circular restricted three-body problem. The first part reveals interplays among invariant manifolds of Lyapunov orbits around the three collinear Lagrange points for high energies. Once energetically forbidden regions vanish, they together form closed separatrices and associated transit orbits cross the unity semi-major axis. The second part extends our previous proposal of using singular collision orbits to find transit orbits reaching the vicinity of the secondary to low energies. A trade-off study indicates that singular collision orbits are more advantageous than invariant manifolds except for very-low-energy regimes.

8:40 **AAS 19-855** **Canonical Transformations via a Sparse Approximation-Based Collocation Method for Dynamical Systems**

Roshan Thomas Eapen, Texas A&M University; Kyle T. Alfriend, Texas A&M University; Manoranjan Majji, Texas A&M University, College Station; Puneet Singla, Pennsylvania State University

The Hamilton-Jacobi equations are extremely useful to facilitate a transformation to a set of coordinates where the dynamics of the system evolve linearly. They also serve as a means of obtaining integrals of motion thereby providing physical insight into the dynamical system. The H-J theory helps to find a canonical transformation, if one exists, by finding the solution of a partial differential equation. In this paper, an approximate value function comprising of an over-complete set of basis functions is used to solve the H-J equation. A nonlinear oscillator is considered as a first example and this method is applied to other complex dynamical systems.

9:00 **AAS 19-744** **Enabling Broad Energy Range Computations at Libration Points Using Isolating Neighborhoods**

Rodney L. Anderson, Jet Propulsion Laboratory/Caltech; Robert Easton; Martin Wen-Yu Lo, Jet Propulsion Laboratory

Isolating blocks have previously been used for computing complete sets of transit trajectories traveling through the L_1 and L_2 libration point gateways in the circular restricted three-body problem. They have also been used to compute close approximations to the hyperbolic invariant sets around the libration points and their associated invariant manifolds. Constructing typical isolating block boundaries can be challenging, and the energy range for which these isolating blocks may be computed is limited. The use of isolating neighborhoods provides a theoretically rigorous approach that eliminates the difficulties involved in constructing isolating block boundaries while expanding the applicable energy range.

9:20 **AAS 19-814** **Transfers from GTO to Sun-Earth Libration Orbits**

Juan Ojeda Romero, Purdue University; Kathleen C. Howell, Purdue University

Rideshare increases launch capabilities and decreases the cost for satellite manufacturers. However, the range of orbits available for secondary payloads is dependent on launch constraints for the primary. Additionally, communications constraints and limited propellant must be incorporated in preliminary mission design for secondary payloads. Ridesharing opportunities are now available for orbit destinations beyond LEO. In this investigation, transfers from GTOs to Sun-Earth Lagrange point orbits are generated using stable manifold transfers and Poincare maps.

9:40 **AAS 19-728** **Accessing Highly Out-of-Ecliptic Science Orbits via Low-Energy, Low-Thrust Transport Mechanisms**

Jeffrey Stuart, Jet Propulsion Laboratory; Rodney L. Anderson, Jet Propulsion Laboratory/Caltech; Christopher Sullivan, University of Colorado Boulder; Natasha Bosanac, University of Colorado, Boulder

Several mission concepts entail the placement of a spacecraft into a high inclination orbit with respect to the solar system ecliptic including solar observatories targeting the polar regions of the Sun or spacecraft seeking an external vantage point on the zodiacal dust cloud of our solar system. In this investigation, techniques for low-thrust and low-energy trajectory design will be integrated into a cohesive framework to access these highly out-of-ecliptic science orbits. A comparison between traditional spacecraft platforms and spacecraft fitting into CubeSat / SmallSat form factors will be made.

10:00 Morning Break

10:20 AAS 19-637 Design and Control of Spacecraft Trajectories in the Full Restricted Three Body Problem

Isabelle Jean, McGill University; Arun K. Misra, McGill University; Alfred Ng, Canadian Space Agency

The DART/Hera mission planned to the binary asteroid system 65803 Didymos has motivated many researchers to understand the dynamics of a spacecraft in the vicinity of binary asteroid systems. The methods to design spacecraft trajectories in this context depend mainly on the way the binary asteroid system is modeled. This study compares the thrust required to maintain the reference trajectory of a spacecraft based on two binary asteroid system models: the first is based on an autonomous version of the model (CRTBP), and the second one is based on the non-autonomous version of the model (FRTBP).

10:40 AAS 19-717 OSIRIS-REx Navigation Small Force Models

Jeroen Geeraert, KinetX; Jason Leonard, KinetX; Patrick Kenneally; Peter Antreasian, KinetX Aerospace; Michael Moreau, NASA Goddard Space Flight Center

The OSIRIS-REx spacecraft arrived at Bennu on December 3rd, 2018 thereby initiating the Preliminary Survey phase consisting of several 7-km altitude flybys of the asteroid. Orbit insertion followed on December 31st, 2018 commencing the Orbital A phase. In this paper the small forces governing the dynamics around the asteroid during these phases are presented in detail. They include: SRP, thermal re-radiation, small forces trending from desaturation maneuvers, and the antenna and LIDAR radiation pressure. Extensive work on modeling these forces has caused the navigation performance to exceed expectations and has reduced the stochastic accelerations below 1e-12 km/s^2.

11:00 AAS 19-785 Asteroid Deflection with Active Boulder Removal

Daniel Brack, University of Colorado Boulder; Jay McMahon, University of Colorado Boulder

An asteroid deflection method by ejecting surface boulders is presented and discussed. The methodology for boulder selection by size and surface location and for boulder launch velocity and timing definition is developed. Boulder launch selection is done with consideration for additional states, mainly rotation and mass distribution. The method is then applied on real asteroids cases for Bennu and Apophis. Secondary effects on the asteroid orbit and rotation through the Yarkovsky and YORP effects are discussed as well.

11:20 AAS 19-798 Stability of highly inclined orbits around the asteroid (153591) 2001 SN263

Diogo Merguizo Sanchez, National Institute for Space Research - INPE; Antonio Fernando Bertachini Prado, INPE

In this work perturbation maps are used to measure the stability of highly inclined orbits around the triple asteroid 2001 SN263, target of the Brazilian ASTER mission. The perturbation maps also provide the delta-v required to keep a spacecraft as close as possible to a Keplerian orbit through orbital maneuvers. The results of this work can be used for the planning of the ASTER mission. The methods presented in this work can be used for the planning of any space mission.

11:40 AAS 19-821 Koopman Operator Theory in Astrodynamics

RICHARD LINARES, Massachusetts Institute of Technology

This paper investigates the application of Koopman Operator (KO) theory as applied to Astrodynamics. The field of astrodynamics has a rich history in motivating the development of techniques in dynamical systems theory, going back to the revolutionary work of Poincaré. Recently, the KO has emerged as a promising alternative to the geometric perspective provided by Poincaré, where the KO formulates the analysis of dynamical systems in terms of observables. This paper investigates this observable based perspective for challenges in the field of astrodynamics.

Aug 13, 2019 Hawthorne

Flight Dynamics, Operations and Atmospheric GN&C

Chair: Brian Gunter, Georgia Institute of Technology

8:00 **AAS 19-928** **Autonomous Satellite Navigation using Intersatellite Laser Communications**

Pratik Dave, Massachusetts Institute of Technology; Kerri Cahoy, Massachusetts Institute of Technology

This work assesses using laser communication (lasercom) intersatellite links to obtain relative position measurements for autonomous navigation. Numerical simulations are used to compare the lasercom crosslink approach with traditional orbit determination methods for example application cases in low Earth orbit (LEO), geostationary Earth orbit (GEO), highly elliptical orbit, and orbits around other planetary bodies. The intersatellite lasercom approach reduces estimated position error by a factor of ten or more, from 100s-1000s of meters to 10s of meters for a GEO satellite, for instance. Use of intersatellite lasercom systems for orbit determination also decreases dependence on Earth-based tracking and navigation systems.

8:20 **AAS 19-619** **Mid-Lift-to-Drag ratio Rigid Vehicle 6-DoF EDL Performance Using Tunable Apollo Powered Descent Guidance**

Breanna Johnson, NASA; Ping Lu, San Diego State University; Christopher Cerimele, NASA Johnson Space Center

The Mid-Lift-to-Drag ratio Rigid Vehicle (MRV) is a candidate in the NASA multi-center effort to determine the most cost effective vehicle to deliver a large- mass payload to the surface of Mars for a human mission. Products of this effort include six-degree-of-freedom (6DoF) entry-to-descent trajectory performance studies for each candidate vehicle. These high fidelity analyses help determine the best guidance and control (G&C) strategies for a feasible, robust trajectory. This paper presents an analysis of the MRV's G&C design by applying common entry and descent associated uncertainties using a Fully Numerical Predictor-corrector Entry Guidance (FNPEG) and tunable Apollo powered descent.

8:40 **AAS 19-797** **Radiometric Autonomous Navigation Fused with Optical For Deep Space Exploration**

Todd Ely, Jet Propulsion Laboratory; Shyam Bhaskaran, Jet Propulsion Laboratory; Jill Seubert, NASA / Caltech JPL; Nicholas Bradley, CalTech / Jet Propulsion Laboratory; Theodore Drain, Jet Propulsion Laboratory

With the advent of the Deep Space Atomic Clock, operationally accurate and reliable one-way radiometric data sent from a radio beacon (i.e., a DSN antenna *or other spacecraft*) and collected using a spacecraft's radio receiver enables the development and use of autonomous radio navigation. This work examines the fusion of radiometric data with optical data to yield more robust and accurate trajectory solutions and the associated navigation algorithms that can be readily adopted for onboard, autonomous navigation. The methodology is characterized using a representative high-fidelity simulation of deep space cruise, approach, and delivery to Mars.

9:00 **AAS 19-747** **THE FIRST COMMERCIAL LUNAR LANDER MISSION: BERESHEET**

John Carrico, Space Exploration Engineering, LLC; Michel Loucks, Space Exploration Engineering (SEE); Haim Shyldkrot, SpaceIL; Eran Shmidt, SpaceIL; Daniela Geron, SpaceIL; Joseph Kronenfeld, SpaceIL; John Taylor, SSC Satellite Management Systems; Lisa Policastri, Space Exploration Engineering (SEE)

On 22 February 2019 SpaceIL's Beresheet spacecraft launched on its way to the Moon atop a Falcon 9 rocket from Florida. This mission is the first commercial mission to the Moon and is done by only the 4th country to attempt a Lunar landing. At the time of writing this abstract (4 April 2019), SpaceIL's Lunar lander, Beresheet, just successfully entered Lunar Orbit, and is planning to land on 11 April. The authors describe the trajectory and maneuver strategy, the navigation plan, and the ground station and tracking network. The on-orbit results are also described and compared with pre-launch the estimate.

9:20 **AAS 19-725** **Improved Atmospheric Estimation for Aerocapture Guidance**

Evan Roelke; Robert Braun, University of Colorado Boulder; Philip Hattis, The Charles Stark Draper Laboratory

Interest in Lunar or Mars-sample return missions encourage innovative orbital operations to save mass and reduce system complexity. Aerocapture, which involves capturing into orbit by flying through a planetary body's upper atmosphere, may provide a significant mass-saving approach for orbital insertion. Drag-modulation guidance architectures drastically reduce system complexity over typical lift modulation systems. However, poor estimation of atmospheric density results in large post-jettison errors in apoapsis altitude. This research investigates estimation technique improvements with density array interpolation and filtering methods in order to make drag-modulated aerocapture a viable architecture for planetary missions.

9:40 AAS 19-638 THE DEVELOPMENT OF AN OPEN-LOOP ANGULAR MOMENTUM UNLOAD METHODOLOGY FOR THE LUNAR RECONNAISSANCE ORBITER AND OF ALGORITHMS TO PREDICT SYSTEM PERFORMANCE

Russell DeHart, KBRwyle

The Lunar Reconnaissance Orbiter is a three-axis stabilized spacecraft launched in 2009. In August 2017, the intensity of one of the miniature inertial measurement unit lasers began to decline and in March 2018 the unit was powered off to reserve what functionality remained for critical activities. Starting in August 2018, the mission began executing open-loop ‘one-shot’ angular momentum unloads, in which operators briefly fire thrusters, waiting for telemetry to settle between firings. This paper presents models predicting cumulative thruster pulses, durations, and imparted delta-Vs for these unloads. Test results obtained when predicting system performance for unloads in 2019 are provided.

10:00 Morning Break

10:20 AAS 19-682 Aerobraking Trajectory Control Using Articulated Solar Panels

Giusy Falcone, University of Illinois at Urbana-Champaign; Zachary Putnam, University of Illinois at Urbana-Champaign

Aerobraking is a set of atmospheric passes through the thermosphere of a planet to remove energy from a spacecraft orbit. This study examines aerobraking at Mars with active steering via articulated solar panels, which are able to provide in-plane control to define the trajectory throughout the atmospheric pass. An online optimal control algorithm is developed to maximize the energy dissipation per atmospheric pass while maintaining a safe thermal environment for the spacecraft. Results indicate active steering with solar panels can significantly improve per-pass energy dissipation, which in turn may reduce the total number of passes required over an aerobraking campaign.

10:40 AAS 19-933 Entry Trajectory Tracking Using Equivalent Elevation State Feedback

Jason Tardy

A new form of entry guidance is proposed which uses target-relative angular state feedback to track a reference trajectory via bank angle modulation. This state consists of an equivalent elevation angle, its derivative, and flight path angle. The mathematics of the state are developed with respect to time and specific energy, and the solution is shown to be unique. For proof-of-concept, a linear quadratic feedback law is used to simulate reference tracking by an HL-20 class vehicle. Results prove the feasibility of this approach and demonstrate implicit range tracking and robustness to dispersions.

11:00 **AAS 19-856** **Estimation of Entry Vehicle Parameters from Trajectory Data**

Kevin Bonnet, University of Colorado at Boulder; Robert Braun, University of Colorado Boulder

The shape of most entry vehicles is defined by a finite set of parameters such as cone angles and various radii. Ranges on these parameters can be estimated from knowledge of a given hypersonic entry trajectory. Combining the equations of motion and analytical formulas for the aerodynamic coefficients, obtained with Newtonian theory, the vehicle's geometric parameters at each point in time are related to known trajectory quantities such as altitude and velocity magnitude. Multiple test cases are analyzed with this approach. A sensitivity analysis to input parameters is also performed. This method can be applied to reconstructed flight data or during vehicle design.

Aug 13, 2019 Winslow Homer

Orbit Determination & Space Surveillance Tracking I

Chair: Puneet Singla, Pennsylvania State University

8:00 **AAS 19-875** **Maximum A Posteriori Estimation of Hamiltonian Systems with High Order Series Expansions**

Simone Servadio, University of Texas at Austin; Renato Zanetti, University of Texas at Austin; Roberto Armellin, University of Surrey

This paper presents a different approach to the Maximum A Posteriori (MAP) estimation method. Thanks to the representation of a probability density function through its Taylor expansion series using Differential Algebra techniques, the research of the best estimate is performed directly on high order polynomials. The presented method has been applied to the high nonlinear problem of Orbit Determination.

8:20 **AAS 19-746** **A Study on Effective Initial Guess Finding Method Based on Bezier Curves: Orbit Determination Applications**

Daegyun Choi, Mississippi State University; Sungwook Yang, Mississippi State University; Henzeh Leeghim, Chosun University; Donghoon Kim, Mississippi State University

Two-point boundary value problems (TPBVPs) are a well-known method to determine orbits of spacecraft for successful missions. However, since its solutions are greatly influenced by how its initial values are selected, an effective method to find initial guesses is required. In this research, the method based on Bezier curves which can effectively draw complex shapes is proposed to find proper initial guesses of TPBVPs. The given TPBVPs are transformed into the nonlinear simultaneous equations using Bezier curves. The appropriate initial guesses are obtained by solving these equations. To validate the performance of the proposed method, numerical simulations are performed.

8:40 **AAS 19-843** **Gaussian Mixture Filter Angles-Only Orbit Determination using Modified Equinoctial Osculating Elements**

Mark Psiaki, Virginia Tech

A Gaussian mixture orbit determination filter is developed using modified equinoctial osculating elements as states. This new filter seeks to reduce the number of Gaussian mixands that are needed to accurately model the Bayesian distributions of angles-only orbit determination. The modified equinoctial elements replace h and k by similar elements that are unbounded. The modified equinoctial state requires the definition of a mixand covariance upper bound for use in the Gaussian mixture filter. In comparison to a position/velocity filter, the new filter reduces the required number of mixands from 5000 to 25 for angles-only orbit determination of a geosynchronous spacecraft.

9:00 **AAS 19-845** **ROBUST PARTICLE FILTER FOR SPACE OBJECTS TRACKING UNDER SEVERE UNCERTAINTY**

Cristian Greco, University of Strathclyde; Lorenzo Gentile, TH Koeln; Massimiliano Vasile, University of Strathclyde; Edmondo Minisci; Thomas Bartz-Beielstein, TH Koeln

This paper presents a robust particle filter approach able to handle a set-valued specification of the probability measures modelling the uncertainty structure of tracking problems. This method returns robust bounds on a quantity of interest compatibly with the infinite number of uncertain distributions specified. The importance particles are drawn and propagated only once, and the bound computation is realised by inexpensively tuning the importance weights. Furthermore, the uncertainty propagation is realised efficiently by employing an intrusive polynomial algebra technique. The developed method is finally applied to the computation of a debris-satellite collision probability in a scenario characterised by severe uncertainty.

9:20 **AAS 19-626** **Computing Gauss-Laplace Equations for Optical Data Processing**

Gim Der, DerAstrodynamics

This paper shows the right way to compute the 2-Body Gauss-Laplace 8th degree polynomial equations, pick the correct root without guessing, and then convert analytically to a perturbed angles-only solution via Vinti-targeting. This perturbed angles-only algorithm is useful for initial orbit determination (IOD) of optical data for space catalog development and SSA, especially for UCT data processing. Most existing angles-only algorithms are 2-Body while the relationship between sensor FOV resolution, data time-span and the Gauss-Laplace equations is ignored, let alone identifing the correct root. This perturbed angles-only algorithm has been tested and verified extensively without failure using GEODSS, GPS and simulated data.

9:40 **AAS 19-643** **Cis-Lunar Navigation Accuracy using Optical Observations of Natural and Artificial Targets**

Nicholas Bradley, CalTech / Jet Propulsion Laboratory; Zubin Olikara, NASA Jet Propulsion Laboratory; Shyam Bhaskaran, Jet Propulsion Laboratory; Brian Young, Jet Propulsion Laboratory, California Institute of Technology.

On-board optical-based autonomous navigation (AutoNav) has the potential to significantly reduce reliance on ground-based assets, and can provide a robust back-up

system for unexpected ground outages. We continue an investigation of AutoNav across the solar system by assessing optical-only navigation performance in cis-lunar space using simulated observations of Moon centers, lunar landmarks, artificial satellites, and asteroids. We show that AutoNav in cis-lunar space is feasible and effective, and that artificial satellites and lunar landmarks are the strongest data types. Optical AutoNav is feasible within current technological capabilities; cis-lunar position uncertainties can be as low as single kilometers.

10:00 Morning Break

10:20 AAS 19-775 **OPTIMAL QUADRATURE BASED FILTERING IN REGULARIZED COORDINATES FOR ORBIT DETERMINATION**

David Ciliberto, The Pennsylvania State University; Puneet Singla, Pennsylvania State University; JOSEPH RAQUEPAS, Air Force Research Laboratory

The development of quadrature based filters for orbit determination and challenges associated with their implementations while using constrained regularized vari- ables in astrodynamics are discussed. Since the regularization process introduces redundant coordinates, a quadrature based method to explicitly account for the state constraints is developed. In particular, a non-product quadrature method known as Conjugate Unscented Transformation will be used for filter develop- ment. Numerical experiments will be conducted to validate the developed filter and results will be compared with linear error theory based filter such as con- strained Kalman filter.

10:40 AAS 19-872 **Consider Filtering Applied to Maneuver Detection for Relative Orbit Determination**

Peter Scarcella, The Pennsylvania State University; Kirk W. Johnson, US Air Force; Joshuah Hess, Air Force Institute of Technology

A Consider Kalman Filter is implemented to add the uncertainty in parameters related both to the quiescent system dynamics and to the maneuver dynamics to a Variable State Dimension filter (VSD). By adding the extra uncertainty from mildly observable parameters related to the maneuver, this approach provides a low-computational-cost improvement over the nominal VSD for orbit determination of an uncooperative spacecraft. Simulations are conducted for a continuously thrusting spacecraft with no a priori knowledge of the maneuver duration. Results have shown improved orbit estimation and thrust levels for both a single model VSD filter and an interacting multiple model VSD.

11:00 AAS 19-625 **Computing Multi-rev Lambert Equations for Radar data Processing**

Gim Der, DerAstrodynamics

This paper presents the right way to compute multi-rev 2-Body Lambert equations, pick the correct multi-rev 2-Body Lambert solution out of 2N+1 without guessing or searching, and then convert analytically to a perturbed Lambert solution via Vinti-targeting. This efficient multi-rev perturbed Lambert algorithm is useful for initial orbit determination (IOD) of radar data for space catalog development and SSA, and is the workhorse for mission planning, station-keeping, satellite rendezvous and docking, formation flying, collision maneuvers, missile targeting, among others. This algorithm has been tested and verified extensively without failure using the NASA2015 debris catalog data.

11:20 **AAS 19-862** **Track Initiation for CubeSat Cluster Deployment Tracking**

John Gaebler, University of Colorado at Boulder; Penina Axelrad

A track initiation scheme is presented that efficiently generates initial conditions for new targets appearing in a surveillance region after a large-scale clustered deployment. Currently in can take days or weeks for all CubeSats to be appear in the space catalog after a deployment. This work assumes initial conditions are unknown and must be estimated from uncorrelated tracks. Pairs of radar observations are used to identify new targets via the Range-Range Constrained Admissible Region approach. These targets are then processed with a Labeled Multi-Bernoulli filter. A simulation of the Planet Labs Flock 3 deployment is used to demonstrate the approach.

11:40 **AAS 19-757** **Root Locus Method of Determining Sensitivity of Polynomial Systems to Error in Orbit Determination Problems**

Kenneth Horneman, Emergent Space Technologies, Inc.; Alex Sizemore, NRC; Alan Lovell; Troy Henderson, Embry-Riddle Aeronautical University; David Zuehlke, Embry-Riddle Aeronautical University; Heidi Darsey, University of New Mexico; Christopher Ertl, Rensselaer Polytechnic Institute

This paper presents an investigation for the behavior of solutions to polynomial systems under the effects of uncertainty using the root locus method. The method is first investigated on a set of two second order polynomials. The method is then extended to two problems in astrodynamics: geolocation of a transmitter from space-based receivers and optical relative orbit determination from space-based observers. Using root loci, a better understanding is ascertained of the effects of various aspects of both problems, including measurement error, receiver or observer location, and changes to design parameters.

2019 Astrodynamics Specialist Conference
Portland, ME, August 11-15, 2019

Aug 13, 2019 Eastland Ball Room

Trajectory Design & Optimization III

Chair: Yanping Guo, JHUAPL

8:00 **AAS 19-851** **LOW THRUST TRANSFERS BETWEEN HALO ORBITS IN THE EARTH-MOON SYSTEM**

Mohammad Azhar, The Pennsylvania State University; Robert Melton, Pennsylvania State University

This paper represents the use of the Particle Swarm Optimization method (PSO) for optimizing the time and propellant consumed in low thrust transfers between Halo Orbits of various amplitudes in the Earth-Moon orbiting satellite system utilizing the Circular restricted 3-body problem dynamics. PSO is a heuristic method, which was used to find the optimum thrust pointing angles and the time of the transfer trajectory. The algorithm was able to determine feasible optimum transfer trajectories between Halo Orbits around Earth-Moon L1 and L2 libration points.

8:20 **AAS 19-816** **Mid-Course Correction Contingency Analysis for James Webb Space Telescope**

Taabish Rashied, A.I. Solutions Incorporated; Benjamin Stringer, a.i. solutions; Jeremy Petersen, a.i. solutions; Karen Richon, NASA GSFC

This investigation will detail two analyses performed as part of an early orbit contingency operations study related to the observatory's inability to maneuver in a sunward direction. First, analysis will be presented detailing the contingency planning developed by the Flight Dynamics Team and shared with the Science and Operations Center to quickly assess the available timeline in the event of a delayed mid-course correction maneuver. Second, the investigation will explore methods for recovering from a maneuver overshoot using spacecraft geometry to exploit the solar radiation pressure perturbation contributions from the large sunshield as well as adjusting the maneuver campaign to recover the observatory.

8:40 **AAS 19-800** **Leveraging NASA's Lunar Gateway and Human Landing System for Low-Cost and Low-Risk Mars Orbital Missions**

Robert Potter, Purdue University; Sarag Saikia, School of Aeronautics and Astronautics, Puurdue University; James Longuski, Purdue

NASA is pushing to have a human presence in lunar orbit in the 2020s and a human landing on the Moon by 2028. This paper outlines three Mars orbital missions in 2033, 2035, and 2037 with excursions to Phobos and Deimos for minimal cost and risk. The missions leverage the same systems used in NASA's proposed Lunar Gateway and Human Landing System. A stop-over and cycler architecture are compared in terms of cost (including hardware, launch, and operations), risk (probability of mission success and crew survival), and logistics (launch manifest and supply aggregation locations).

9:00 AAS 19-834 Exploration of IMAP Science Orbit Design Space to Balance Nominal and Extended Mission Trades

AMANDA HAAPALA CHALK, JHU Applied Physics Lab; Fazle Siddique, Johns Hopkins University Applied Physics Laboratory

The Interstellar Mapping and Acceleration Probe (IMAP) mission, planned for launch in 2024, will place a spacecraft in a Sun-Earth L1 Lissajous orbit to study the boundary of the heliosphere that encapsulates and protects our solar system. The nominal mission is planned for 2 years, with an extended mission expected to continue the science and space weather objectives. While the design space is relatively small, the mission costs can vary significantly. Here, studies of the multidimensional trade space are presented that enable selection of the optimal science orbit that balances the needs of both the nominal and extended missions.

9:20 AAS 19-767 Missed Thrust Analysis for a Potential Mars Sample Return Orbiter

Jose Manuel Sanchez Perez, ESA; Gábor Varga, European Space Agency

Studies for an international NASA-ESA Mars Sample Return consider a hybrid Earth Return Orbiter capable of performing chemical Mars orbit insertion and using elsewhere solar electric propulsion in order to achieve its mission. This work presents the approach to analyse the impact of unplanned outages producing missed thrust in the outbound and inbound heliocentric transfers. Safe mode statistics from NASA missions and an iterative trajectory optimisation process enable a probabilistic analysis using Monte Carlo simulation. Results of the analysis are fundamental to assess the adequacy of propellant and time margins used in trajectory design.

9:40 AAS 19-618 End to End Optimization of a Mars Hybrid Transportation Architecture

Min Qu, AMA; Raymond Merrill, NASA Langley Research Center; Patrick Chai, NASA Langley Research Center

NASA's Mars Study Capability Team (MSCT) is developing a reusable Mars hybrid transportation architecture in which both chemical and solar electric propulsion systems are used in a single vehicle design to send crew and cargo to Mars. This paper presents a new integrated framework that combines Earth departure/arrival, heliocentric trajectory, Mars orbit reorientation, and vehicle sizing into a single environment and solves the entire mission from beginning to end in an effort to find a globally optimized solution for the hybrid architecture.

10:00 Morning Break

10:20 AAS 19-633 Optimization of the Lucy Interplanetary Trajectory via Two-Point Direct Shooting

Jacob Englander, NASA Goddard Space Flight Center; Donald Ellison, NASA Goddard Space Flight Center; Kenneth Williams, KinetX Aerospace, Inc.; Jim McAdams, KinetX, Inc.; Jeremy Knittel, KinetX Aerospace, Inc.; Brian Sutter, Lockheed-Martin; Chelsea Welch, Lockheed-Martin Space Systems; Dale Stanbridge, KinetX Aerospace; Kevin Berry, NASA Goddard Space Flight Center

Lucy is NASA's next Discovery class mission and will explore the Trojan asteroids in the Sun-Jupiter L4 and L5 regions. This paper details the design of Lucy's interplanetary trajectory using a direct two-point shooting transcription, nonlinear programming, and monotonic basin hopping. These techniques are implemented in the Evolutionary Mission Trajectory Generator (EMTG), a trajectory optimization tool developed at NASA Goddard Space Flight Center. We present applications to the baseline trajectory design, Monte-Carlo analysis, and operations.

10:40 AAS 19-918 Enabling Sustainable Human Exploration of Mars via an Orbital Logistics Node

Rachana Agrawal, Purdue University; Robert Potter, Purdue University; Sarag Saikia, School of Aeronautics and Astronautics, Puurdue University; James Longuski, Purdue

To enable sustainable human exploration of Mars, supply chains are crucial and must have nodes at critical locations such as the Earth's surface, Earth's orbit, Cis-lunar space, Mars' orbit and the surface of Mars. We describe one such logistics node in orbit around Mars with aggregation, refueling and refurbishing capabilities. We present trades associated with a human mission using an orbital node and how their study will help assess the node's viability. Though all trades need to be studied, the logistics node parking orbit is found to be a critical one that affects all the phases of the mission.

11:00 AAS 19-799 Survey of Twenty Unique Low-Thrust Earth-Mars Cycler Geometries

Robert Potter, Purdue University; James Longuski, Purdue

Twenty Earth-Mars cycler geometries are investigated to produce a Pareto frontier for mission designers. The number of cycler geometries investigated was based on three criteria: 1) a maximum of four vehicles to cover every crewed Earth-to-Mars and Mars-to-Earth transfer, 2) an average of less than 1 km/s of ΔV required per synodic period

(2.1 years), and 3) a low-thrust propulsion system with a thrust-to-weight ratio of 0.1 N/Mg. We have identified six cyclers that span the frontier with the most desirable characteristics and trade-offs between crewed time-of-flights, planetary flyby velocities, required ΔV, and the number of vehicles.

Aug 13, 2019 Rines A

AIAA Committee Lunch

Aug 13, 2019 Eastland Ball Room

Asteroid & Non-Earth Orbiting Missions I

Chair: Ossama Abdelkhalik, Iowa State University

13:30 AAS 19-876 Experimental Field Testing and Confirmation of Particle Swarm Optimization for Autonomous Extraterrestrial Surface Search and Exploration

Gregory Hatfield, University of New Hampshire; Alex Cook, University of New Hampshire; May-Win Thein, University of New Hampshire

Particle Swarm Optimization (PSO) is a heuristic optimization technique that was originally conceived by trying to mimic swarms of animals in nature. In previous works at the University of New Hampshire, the authors have examined an autonomous methodology for the generic search mission on extraterrestrial surfaces via Particle Swarm Optimization. In this paper, the authors propose to apply the developed techniques to a fleet of ground-based robots as proof-of-concept for the efficacy of the PSO methods. It is expected that these experimental results will show that PSO as an effective method in future space exploration.

13:50 AAS 19-761 Fast Estimation Method for Trajectories to Near-Earth Asteroids

Lorenzo Casalino, Politecnico di Torino - DIMEAS; Luigi Mascolo, Politecnico di Torino; Alessandro Bosa, Politecnico di Torino

A novel approach for preliminary evaluation of minimum-propellant trajectories to Near-Earth Asteroids is presented. Multiple burn arcs are performed in correspondence of the apses of the target to change the initial spacecraft orbit into the desired target orbit.
The propellant consumption of each basic maneuver is estimated by a procedure based on Edelbaum's approximation, adapted for short arcs. Only numerical solution of a three-unknown algebraic system is needed, making the procedure extremely fast.
The accuracy of the proposed method is demonstrated by comparing the results with solutions obtained with an indirect optimization method for a large number of NEAS.

14:10 AAS 19-623 Initial Near-Earth Object Accessibility Insights From The NHATSchecker Utility

Daniel Adamo

The NHATSchecker utility is independently spawned from Near-Earth Object Human Space Flight Accessible Targets Study (NHATS, pronounced "gnats") software documentation as a means to assess that software baseline's output reproducibility and

to study effects from contemplated capability changes. Evaluating accessibility for specific near-Earth object destinations as examples, NHATSchecker processing provides multiple insights relevant to NHATS users and software developers alike. Initial insights from these examples are documented herein.

14:30 AAS 19-738 Multi-Arc Filtering During the Navigation Campaign of the OSIRIS-REx Mission

Andrew French, University of Colorado ; Jason Leonard, KinetX; Jeroen Geeraert, KinetX; Brian Page, KinetX Aerospace, Inc.; Peter Antreasian, KinetX Aerospace; Michael Moreau, NASA Goddard Space Flight Center; Jay McMahon, University of Colorado Boulder; Daniel Scheeres, Colorado Center for Astrodynamics Research; Dante Lauretta, OSIRIS-REx

The Navigation Campaign of the OSIRIS-REx mission consisted of three phases: Approach, Preliminary Survey and Orbital A. The standard orbit determination filtering techniques used to navigate the spacecraft were unable to fit data from these three phases simultaneously due to numerical issues associated with the nonlinear dynamics and the long arc length. Consequently, a multi-arc filtering algorithm was implemented in order to combine the information from each of these arcs. Multi-arc solutions for Bennu’s spin state and gravity field are presented here.

14:50 AAS 19-762 Design and Reconstruction of the Hayabusa2 Precision Landing on Ryugu

Shota Kikuchi, Japan Aerospace Exploration Agency; Fuyuto Terui, ISAS/JAXA; Naoko Ogawa, Japan Aerospace Exploration Agency; Takanao Saiki, JAXA / ISAS; Go Ono, Japan Aerospace Exploration Agency; Kent Yoshikawa, Japan Aerospace Exploration Agency; Yuto Takei; Yuya Mimasu, Japan Aerospace Exploration Agency; Hitoshi Ikeda, Japan Aerospace Exploration Agency; Hirotaka Sawada, Japan Aerospace Exploration Agency; Tomokatsu Morota, Nagoya University; Naru Hirata, Aizu University; Naoyuki Hirata, Kobe University; Toru Kouyama, National Institute of Advanced Industrial Science and Technology; Shingo Kameda, Rikkyo University; Yuichi Tsuda, Japan Aerospace Exploration Agency

The Hayabusa2 spacecraft successfully landed on the asteroid Ryugu on February 22nd, 2019 . Because of the abundance of boulders, the touchdown operation required high accuracy for spacecraft safety. This research, therefore, investigates a precision landing sequence using retroreflective marker tracking. The trajectory for the touchdown operation is computed based on a high-fidelity gravity model to minimize the landing error. In addition, this paper provides landing dispersion analysis results for the evaluation of touchdown safety. Consequently, it is demonstrated that a landing accuracy of 3 m can be achieved, resulting in the successful touchdown.

15:10 AAS 19-676 OSIRIS-REX NAVIGATION CAMPAIGN TRAJECTORY DESIGN AND MANEUVER PERFORMANCE

Daniel Wibben, KinetX, Inc.; Andrew Levine, KinetX, Inc.; Samantha Rieger; Jim McAdams, KinetX, Inc.; Peter Antreasian, KinetX Aerospace; Jason Leonard, KinetX; Michael Moreau, NASA Goddard Space Flight Center; Dante Lauretta, OSIRIS-REx

The first six months of asteroid proximity operations for the OSIRIS-REx mission is known as the Navigation Campaign – a portion of the mission designed to optimize initial characterization of asteroid Bennu and its dynamical environment in support of initial orbit insertion and transition from star-based to landmark-based optical navigation. During this time, the spacecraft executed sixteen maneuvers across a large range of delta-V magnitudes. This work discusses the spacecraft trajectory design of the Navigation Campaign, which enabled the collection of critical information that led to the achievement of these milestones, and a summary of the performance of executed maneuvers.

15:30 AAS 19-886 Navigation Preparations for a Possible Binary System During the New Horizons Extended Mission

Joel Fischetti, KinetX Aerospace; John Pelgrift, KinetX, Inc.; Erik Lessac-Chenen, KinetX Aerospace, Inc.; Jeremy Bauman, KinetX inc.; Derek Nelson, KinetX, Inc.; Dale Stanbridge, KinetX Aerospace; Michael Salinas, KinetX Aerospace; Peter Wolff, KinetX Aerospace, Inc.; Bobby G. Williams, KinetX, Inc.; Frederic Pelletier, NorthStar Earth and Space; Mark Holdridge, Johns Hopkins APL; H. A. Weaver, Johns Hopkins Univ. Applied Physics Lab; John Spencer, Southwest Research Institute; Simon Porter, Southwest Research Institute; Marc Buie, Southwest Research Institute; Cathy Olkin; Alan Stern, Southwest Research Institute

The New Horizons spacecraft recently completed the most distant close flyby in spaceflight history during its encounter with (486958) 2014 MU69, a Kuiper Belt Object (KBO). The image resolution necessary to determine whether MU69 was a single body or binary system was not attainable until days before encounter. This presented a challenge for navigation, as the mission needed to be prepared for the possible discovery and subsequent orbit determination of a binary system up until encounter. This paper presents the algorithm development, simulations, and results of operational readiness tests in preparation for a binary system.

15:50 AAS 19-641 Spacecraft Asteroid Hovering using Udwadia-Kalaba Formulation with Time-Varying Coefficients

Wesley Stackhouse, Embry-Riddle Aeronautical University; Morad Nazari, Embry-Riddle Aeronautical University; Troy Henderson, Embry-Riddle Aeronautical University; Tansel Yucelen, Department of Mechanical Engineering, University of South Florida

The dynamics and control of a spacecraft hovering over an asteroid are observed and implemented using the Udwadia-Kalaba (UK) constrained motion analysis. The equations of the constraints for a spacecraft to converge to and remain at a hover point over an asteroid are derived. Then, the exact forces required to satisfy and maintain those constraints are obtained using the UK formulation including gravitational perturbations of the asteroid. These forces can then be used as a benchmark to justify those obtained using different control strategies.

Aug 13, 2019 Hawthorne

High Performance Computing, Large Space Structures & Tethers

Chair: Fabio Curti, School of Aerospace Engineering

13:30 AAS 19-874 Cloud Computing Methods for Near Rectilinear Halo Orbit Trajectory Design

Diane Davis, a.i. solutions, Inc.; Sean Phillips, Johns Hopkins University Applied Physics Labs

A proposed Gateway facility in a lunar Near Rectilinear Halo Orbit (NRHO) will serve as an outpost in deep space, with spacecraft periodically arriving and departing. As spacecraft depart from the Gateway, recontact analysis must be performed to ensure safe operations. Escape dynamics from NRHOs are governed by multiple gravitational bodies, yielding a trajectory design space that is exhaustively large. This paper summarizes the recontact analysis for departure from the NRHO and describes how the Deep Space Trajectory Explorer (DSTE) trajectory design software incorporates high performance Cloud computing to compute and visualize the orbit design space.

13:50 AAS 19-794 NLPAROPT: A Parallel Nonlinear Programming Solver - Applications to Spacecraft Trajectory Optimization

Ryne Beeson, University of Illinois at Urbana-Champaign; Patrick Haddox, CU Aerospace; Samah Karim, University of Illinois at Urbana-Champaign; Bindu Jagannatha, CU Aerospace LLC; Deivn Bunce, University of Illinois at Urbana Champaign; Kyle Cochran, University of Illinois at Urbana-Champaign; Edgar Solomonik, University of Illinois at Urbana-Champaign; Alexander Ghosh, University of Illinois at Urbana-Champaign

We present ongoing research and development on a new parallel nonlinear programming solver, NLPAROPT, that is being developed by CU Aerospace with collaboration from the University of Illinois at Urbana-Champaign.

The solution of a nonlinear program is at the heart of many optimal control software packages.

All available nonlinear programming solvers are inherently serial, with trivial parallelism or parallelism that is not necessary holistic.

We present the overall architecture, discuss how structure from the dynamic optimization problem can be exploited and present current results on spacecraft trajectory optimization problems.

14:10 AAS 19-793 Robust Optimal Fuzzy Sun-Point Control of a Large Solar Power Satellite Subject to Actuators Amplitude and Rate Constraints

Chokri Sendi, University of Alaska Anchorage; Antonio Won, University of Alaska Anchorage; Luke McCue, University of Alaska Anchorage

This paper focus on the control design for attitude stability of a large solar power spacecraft. The solar sail experiences external disturbances due to the solar pressure, gravity-gradient moment, atmospheric drag, magnetic torques, and model uncertainties. Therefore one of the main features of the designed fuzzy controller is to be made robust to withstand uncertainties, disturbances and to guarantee the Sun-pointing accuracy of the spacecraft. It should be noted that the designed controller stabilizes the attitude despite the fact that the spacecraft dynamic is subject to actuators amplitude and rate saturation.

14:30 AAS 19-639 A Unified Formulation for State-Space Based Recovery of Mass, Stiffness, and Damping Matrices

Minh Phan, Dartmouth College; Dong-Huei Tseng; Richard Longman, Columbia University

This paper provides a unified formulation to recover a structure mass, stiffness, and damping matrices from its identified state-space model. In previous formulations, displacement, velocity, or acceleration measurements are treated as three separate cases where displacement measurement is mathematically the simplest yet the least practical, and acceleration measurement is the most practical yet mathematically the most complicated. In this paper, a unified solution is offered where velocity and acceleration measurements are handled in the same manner as displacement measurement, thus the resultant algorithms are simplified significantly.

14:50 AAS 19-864 Design of a Distributed Modular Attitude Controller for Spacecraft Composed of Reconfigurable Joined Entities with Compliant Coupling

Deepti Kannapan, The Aerospace Corporation

We present a procedure for designing a simple distributed attitude control system for a reconfigurable spacecraft composed of joined entities, which are relatively rigid compared to the compliant interfaces between them. This problem is challenging due to flexible modes of the spacecraft, caused by the compliant interfaces, and inertial properties that take an ensemble of values as the spacecraft reconfigures.

We frame the problem as: pre-selecting control parameters and mechanical properties of the interfaces to ensure stability and performance for an ensemble of required configurations of the spacecraft, by identifying and designing for a bounding "worst-case" configuration from the ensemble.

15:10 AAS 19-783 VALIDATION OF SIMULATION OF SPACE NET DEPLOYMENT PHASE WITH PARABOLIC FLIGHT EXPERIMENT DATA

Rachael Gold , University at Buffalo ; Eleonora Botta, University at Buffalo

A proposed solution to capture large debris is tether nets. This paper validates a simulator for the deployment of a net in space, implemented with the multibody dynamics simulation tool Vortex Dynamics. The dynamics of the simulated net, modeled with a lumped parameter approach, is compared to data taken during a parabolic flight experiment. Results show good agreement between the trajectory of the net in the experiment and in the simulation, when residual gravitational and Coriolis acceleration are accounted for. These results imply that the simulator can be confidently used to study the deployment dynamics of nets in space.

Aug 13, 2019 Main Lobby

Registration

Aug 13, 2019 Longfellow

Special Session: GTOC - X (Global Trajectory Optimization Competition)

Chair: Anastassios Petropoulos, NASA / Caltech JPL

13:30 AAS 19-891 GTOC X: Settlers of the Galaxy Problem Description and Summary of the Results

Anastassios Petropoulos, NASA / Caltech JPL; Eric Gustafson, NASA / JPL Caltech; Gregory Whiffen, NASA / Caltech JPL; Brian Anderson, NASA / Caltech JPL

In about ten thousand years from the present, humanity will reset its counting of years to zero. Year Zero will be the year when humanity decides the time is ripe for the human race to boldly venture into the galaxy and settle other star systems. One hundred thousand star systems in the galaxy have been identified as being suitable for settlement. Even in this Year Zero, although technologies and knowledge have dramatically progressed, we are still subject to the tyranny of inertia and remain far from the near-instantaneous space travel depicted fancifully in science fiction. However, enormous strides have been made in the ability to live in space, so much so that self-reliant settler vessels can travel though space for hundreds of thousands of generations, making it possible for humans to reach and settle other star systems. The task in GTOC X is to settle as many of the one hundred thousand star systems as possible, in as uniform a spatial distribution as possible, while using as little propulsive velocity change as possible.

13:50 AAS 19-894 GTOC X: Solution approach of Team Sapienza-PoliTo

Alessandro Zavoli; Lorenzo Federici, Sapienza University of Rome; Boris Benedikter, Sapienza University of Rome; Lorenzo Casalino, Politecnico di Torino - DIMEAS; Guido Colasurdo, Università di Roma Sapienza

This paper provides an overview of the solution approach and the numerical methods developed by the joint team Sapienza University of Rome and Politecnico di Torino (Team Sapienza-PoliTo) in the context of the 10th Global Trajectory Optimization Competition, also known as GTOC X. The proposed problem, named Settlers of the Galaxy, represents a unique challenge, where participants are asked to design a settlement tree for colonizing the galaxy, i.e., a pool of one hundred thousand candidate stars, scoring points according to a prescribed merit function J, that rewards large settlements, uniformly distributed in space. An ecient use of propulsion is also taken into account as a multiplicative premium factor. Solutions submitted earlier in the competition are also slightly rewarded.

14:10 AAS 19-902 Settler of the Galaxy: The CSU Solution to GTOCX

Chen Zhang, Technology and Engineering Center for Space Utilization, Chinese Academy of Sciences; Chihang Yang, Technology and Engineering Center for Space Utilization, Chinese Academy of Sciences,; Hao Zhang, Technology and Engineering Center for Space Utilization, Chinese Academy of Sciences; RENYONG ZHANG, Technology and Engineering Center for Space Utilization, Chinese Academy of Sciences; Hao Peng, Rutgers, The State University of New Jersey; Gao Yang

This work describes the solution to the 10th Global Trajectory Optimisation Competition (GTOC-X) found by the Center for Space Utilization of the Chinese Academy of Sciences. It is expected to settle as many of the one hundred thousand star systems as possible during 90 million years, and a uniform spatial distribution is desired at the end of the mission. The exponential growth in options as the settlement tree grows, coupled with a merit function does not increases monotonically with the number of settled stars, makes difficult to guide the tree expansion with a simple strategy directly. In this paper, we provide a systematic design methodology of the generation of settlement tree, and our team finally got the sixth place and reached a score of 1111.01 points.

14:30 AAS 19-896 GTOC X: Methods and Results from the HIT_BACC Team

Ouyang Qi, Beijing Aerospace Control Center; Yong Liu, Beijing Aerospace Control Center; Pengfei Cao, Beijing Aerospace Control Center; zichen fan, Harbin Institute of Technology ; Yabo Hu, Harbin Institute of Technology; Cunyan Xia, Harbin Institute of Technology; Gang Zhang, Harbin Institute of Technology

This paper presents the methods proposed by the team 46 (Joint team of Harbin Institute of Technology and Beijing Aerospace Control Center) in the 10th Global Trajectory Optimization Competition (GTOCX). The task in GTOCX is to settle the star systems in the galaxy. The objective is to settle as many star systems as possible, in as uniform a spatial distribution as possible, while using as little propulsive velocity change as possible.

14:50 AAS 19-897 GTOC X: Our Plan to Settle the Galaxy (ESA-ACT)

Dario Izzo, European Space Agency; Marcus Märtens, European Space Agency; Ekin Öztürk, European Space Agency; Mate Kisantal, European Space

Agency; Kostas Konstantinidis, ESA; Luís Simoes, ML Analytics; Chit Hong Yam, ispace, inc.; Javier Hernando-Ayuso, ispace, inc.

The 10th edition of the Global Trajectory Optimization Competition (GTOC X) invited participants all over the world to compete against each other to design efficient missions with the goal to settle our galaxy. Leveraging concepts of interstellar space travel like generational ships, the participants were tasked to develop settlement plans as each newly settled star system could spawn new settlement ships. This work presents the solution strategies developed by the ESA-ACT during the month long competition. In particular, we unfold the mathematical structure of the objective function that demanded a uniform spreading throughout the galaxy and discuss its implications. We describe a tree search that is able to grow settlement trees concurrently over time starting from multiple initial points. Furthermore, we deploy several techniques to rearrange already established settlement trees in order to reduce the overall propulsive velocity change required.

15:10 **AAS 19-898** **GTOC X: Results and Methods of Team 38 - Tsinghua & XINGYI**

Zhibo E, School of Aerospace Engineering Of Tsinghua University; Di Wu, Tsinghua University; Haiyang Li, Politecnico di Milano; Tsinghua University; Anastassios Petropoulos, NASA / Caltech JPL

This paper summarizes our computing methods and results of solving GTOC X problem. The GTOC X problem is referred to settlement of one hundred thousand suitable galaxy star systems during 90 million years. Solving such a large-scale problem requires tremendous amount of calculation. To overcome this difficulty, our team proposed a series of optimization strategies based on genetic algorithm. First, we design a partitioning strategy to generate the initial set of settlement stars, which are settled by fast ships and mother ships. Then, a multiple phase optimiza-tion strategy based on genetic algorithm is proposed to generate substantial settle-ment stars. After that, in order to decrease the fuel consumption, a local optimiza-tion method is applied to exchange different transfers. Finally, fuel consumption of all the transfers are optimized by NPSOL and PSO. The final score of our team’s results is 2070.53.

15:30 **AAS 19-899** **GTOC X: Results and Methods of National University of Defense Technology and Xi'an Satellite Control Center**

Ya-Zhong Luo, National University of Defense Technology; Hong-Xin Shen, Chinese Xi'an satellite control center; An-Yi Huang, National University of Defense Technology; Tian-Jiao Zhang, Chinese Xi'an satellite control center; Yue-He Zhu, National University of Defense Technology; Zhao Li, Chinese Xi'an satellite control center; Peng Shu, National University of Defense

Technology; Zhen-Jiang Sun, National University of Defense Technology; Jian-Hui Li, Chinese Xi'an satellite control center; Zhen-Yu Li, National University of Defense Technology; Jian-Jun Shi, National University of Defense Technology; Bing Yan, National University of Defense Technology; Xiang-Nan Du, National University of Defense Technology; Zhen Yang, National University of Defense Technology

The 10th global trajectory optimization competition (GTOC X) problem is the settlement of the galaxy. This was accomplished by three mother ships and two fast ships flying around the galactic center. The goal was to settle as many of the one hundred thousand star systems as possible, in as uniform a spatial distribution as possible, while using as little propulsive velocity change as possible. A performance index, which depended on the number of targets, the distribution of the targets, the ΔV ratio, must be maximized subject to a variety of constraints. Propulsive maneuvers are impulsive, with ΔVs magnitude and number limits; the tour should last less than 90 Myr (million years) in a 10 Myr launch window. The methods used by the team NUDT&XSCC are described, along with the winning solution found by the team.

15:50 **AAS 19-900** **GTOC X: General Question and Answer Session**
Anastassios Petropoulos, NASA / Caltech JPL

General Questions and Answers for GTOC-X

16:10 **AAS 19-901** **GTOC X: Trophy Award Presentation**
Anastassios Petropoulos, NASA / Caltech JPL

Trophy Presentation for GTOC-X

Aug 13, 2019 Winslow Homer

Special session: NASA CARA CA Requirements Development Initiative

Chair: Alinda Mashiku, NASA GSFC, Matthew Hejduk, Astrorum Consulting LLC

13:30 **AAS 19-668** **NASA Conjunction Assessment Risk Analysis Updated Requirements Architecture**
Lauri Newman, NASA Goddard Space Flight Center; Alinda Mashiku, NASA GSFC; Matthew Hejduk, Astrorum Consulting LLC; Megan Johnson, a.i. Solutins, Inc.; Joseph Rosa, Omitron, Inc.

In response to recent developments in Space Situational Awareness, NASA CARA has pursued a multi-year evaluation initiative to re-examine risk assessment algorithms and techniques, to develop improvements, and to assemble analysis-based operational requirements. This paper gives an overview of the principal parts of the CA risk assessment process used at NASA CARA, outlines the technical challenges that each part presents, surveys the possible solutions, and then indicates which particular solution is being recommended for NASA. The paper concludes with an inventory of remaining important open research questions and statements of the operational utility that would be engendered by their solutions.

13:50 **AAS 19-702** **Recommended Methods for Setting Mission Conjunction Analysis Hard Body Radii**
Alinda Mashiku, NASA GSFC; Matthew Hejduk, Astrorum Consulting LLC

For real-time operations, conjunction risk analysis that involves computing the probability of collision typically depends on the state vector, its covariance, and the combined hard body radius (HBR) of both the primary and secondary objects. However, most algorithmic approaches that compute the Probability of Collision (Pc) use generic conservative default values for HBRs that may tend to go beyond the physical limitations of the combined objects.The goal of this analysis is to demonstrate the various calculated Pc values obtained based on a HBR for aa primary object with known attitude information, oriented in the encounter conjunction plane at closest approach.

14:10 **AAS 19-612** **Assessing GEO and LEO Repeating Conjunctions Using High Fidelity Brute Force Monte Carlo Simulations**
Luis Baars, Omitron, Inc.; Doyle Hall, Omitron, Inc.; Steve Casali, Omitron, Inc.

Probability of collision (P_c) estimates for Earth-orbiting satellites typically assume a temporally isolated conjunction event. However, under certain conditions two objects may experience multiple close approach events over the course of hours or days. In these repeating conjunction cases, the P_c accumulates as each successive encounter occurs. The NASA Conjunction Assessment Risk Analysis team has updated its "brute force Monte Carlo" (BFMC) software to accurately estimate such accumulating P_c values for repeating conjunctions. This paper describes the updated BFMC algorithm and discusses the implications for conjunction risk assessment.

14:30 AAS 19-652 Satellite Collision 'Probability,' 'Possibility,' and 'Plausibility': A Categorization of Competing CA Risk Assessment Paradigms
Matthew Hejduk, Astrorum Consulting LLC; Dan Snow, Omitron Inc.

While the probability of collision (Pc) is the standard conjunction assessment risk metric, it contains known shortcomings, such as potential understatement of risk in situations of poor data quality. A number of alternative metrics/approaches exist, each with their own advantages and disadvantages. The present study examines the CA risk assessment dynamic and identifies the tacit hypothesis testing that it employs. It then examines the mainstream alternatives to Pc, categorizing them as probability-, possibility-, and plausibility-based constructs and indicating how the use of such approaches alters the null hypothesis construction. The study concludes with recommendations for operational use and further study.

14:50 AAS 19-669 An Operational Algorithm for Evaluating Satellite Collision Consequence
Travis Lechtenberg, Omitron Inc.

Risk is properly considered as the combination of likelihood and consequence; but CA has usually limited itself to the consideration of only collision likelihood. When considered from an orbital corridor protection perspective, the focus shifts to the question of the amount of debris that a collision might produce (the "consequence"). The present paper presents an operational algorithm for determining the expected amount of debris production should a conjunction result in a collision and assessing the algorithm's fidelity against a database of characterized objects.

15:10 AAS 19-671 MULTIVARIATE NORMALITY OF CARTESIAN-FRAMED COVARIANCES: EVALUATION AND OPERATIONAL SIGNIFICANCE
Travis Lechtenberg, Omitron Inc.

CA relies on representative Cartesian uncertainty volumes in order to calculate probabilities of collision. Among the potential shortcomings of a covariance matrix representation of state errors, the most worrisome is the coordinate mismatch between the Cartesian framework in which these matrices are distributed and the curvilinear path that satellite orbits actually follow. The present study compares curvilinear-based and Cartesian covariance representations for ~50,000 conjunctions to determine the frequency in which significant deviations from Gaussianity are observed, then compares the 2-D Pc result from the Cartesian covariance to a Monte Carlo Pc conducted in element space to assess operational significance.

15:30 AAS 19-631 Determining Appropriate Risk Remediation Thresholds from Empirical Conjunction Data Using Survival Probability Methods

Doyle Hall, Omitron, Inc.

Satellites sometimes maneuver before conjunctions to remediate the risk of an on-orbit collision. Many missions use probability of collision (Pc) thresholds to decide when such maneuvers should be performed. These thresholds tend to be conservative because of policies that require satellites survive their lifetimes without collision with high confidence (e.g., 99.9%). This study presents a semi-empirical method to estimate remediation Pc thresholds that satisfy such lifetime risk requirements. The formulation combines survival probability analysis with empirical conjunction histories to estimate remediation thresholds as a function of satellite size, remaining on-orbit duration, lifetime collision probability limit, collision consequence, and other parameters.

15:50 AAS 19-632 Implementation Recommendations and Usage Boundaries for the Two-Dimensional Probability of Collision Calculation

Doyle Hall, Omitron, Inc.

The two-dimensional (2D) probability of collision (Pc) estimation method relies on several assumptions that must be satisfied for accurate results. Monte Carlo analysis of ~44,000 conjunctions indicates that 2D-Pc provides accurate estimates for most typical conjunctions, but occasionally underestimates Pc significantly, indicating an assumption violation. A test to detect large-amplitude underestimation inaccuracies can be based on how much “offset-from-TCA” 2D-Pc values vary during a well-defined time interval bracketing closest approach. The test successfully detects all large-amplitude 2D-Pc underestimations found to date, with a moderately high false-alarm rate. The analysis also provides implementation recommendations and usage boundaries for the 2D-Pc method.

Aug 13, 2019 Portland Ocean Gateway

Portland Ocean Gateway Offsite Event

Aug 14, 2019 Main Lobby

Registration

Aug 14, 2019 Longfellow

Asteroid & Non-Earth Orbiting Missions II

Chair: Diane Davis, a.i. solutions, Inc.

8:00 **AAS 19-819** **NASA Goddard Independent Navigation Results for OSIRIS-REx Initial Encounter at Bennu**

Dolan Highsmith, The Aerospace Corporation; Andrew Liounis, NASA Goddard Space Flight Center; Kenneth Getzandanner, NASA Goddard Space Flight Center; Jason Swenson, NASA Goddard Space Flight Center; Benjamin Ashman, NASA Goddard Space Flight Center; Jeffrey Small, The Aerospace Corporation; Jennifer Donaldson, NASA Goddard Space Flight Ceter; David Rowlands, NASA Goddard Space Flight Center; Erwan Mazarico, Massachusetts Institute of Technology / EAPS; Michael Moreau, NASA Goddard Space Flight Center; Jason Leonard, KinetX; Coralie Adam, KinetX, Inc.; Peter Antreasian, KinetX Aerospace; Dante Lauretta, OSIRIS-REx

Throughout OSIRIS-REx's initial encounter with asteroid Bennu, a variety of optical navigation and orbit determination processes were used in support of spacecraft operations. The OSIRIS-REx Flight Dynamics Team consists of engineers from KinetX Aerospace, NASA Goddard Space Flight Center, and the Aerospace Corporation working as an integrated team. While KinetX is responsible for a majority of the official navigation deliveries, NASA personnel perform independent assessments of navigation performance with Goddard heritage tools, while also providing surge support for operations. This paper describes the Goddard independent navigation effort and highlights results from the Approach, Preliminary Survey,and Orbital A mission phases.

8:20 **AAS 19-756** **Earth-Moon Halo Orbit – Gateway or Tollbooth?**

David Dunham, KinetX, Inc.; Kjell Stakkestad, KinetX Aerospace, Inc.; Jim McAdams, KinetX, Inc.; Anthony Genova, NASA; Jerry Horsewood, SpaceFlightSolutions, Inc.

Robert Farquhar promoted a lunar halo-orbit station in 1971 and in 2004. This idea is now popular for a lunar "gateway". A "Moon direct" approach is more efficient if the goal is only exploration of the lunar surface. For human missions to Mars, a high-energy lunar halo orbit is ideal for a reusable Deep Space Transport (DST) between missions. The "Gateway" might be changed to a DST; building only one habitat provides large savings. "Phasing orbit rendezvous" for exploration by the DST, might also be used for astronaut repair of space observatories that normally operate in the Sun-Earth L2 region.

8:40 **AAS 19-709** **Sensitivity of Trajectories to Mass Parameters in the Restricted Full Three Body Problem**

Alex Davis, University of Colorado Boulder; Daniel Scheeres, University of Colorado Boulder

In support of future missions to binary asteroids, such as DART and HERA, we study the sensitivity of spacecraft in the restricted full three body problem (RF3BP) to the mass parameters and geometry of the target system.

9:00 **AAS 19-678** **Autonomous Estimation of Spin and Shape of a Small Body via Extended Target Tracking**

Enrico Zucchelli, The University of Texas at Austin; Brandon Jones, University of Texas at Austin; Ryan Russell, The University of Texas at Austin

It is desired to enable missions to small bodies for which prior information about shape and spin is unavailable. We present a recursive approach to simultaneously estimate shape and spin axis and rate of an asteroid using LIDAR as a first study and optical images from a monocular camera as a second study. We treat the asteroid as a target and leverage the extended target tracking framework, providing a Bayesian description of the shape. We test the method on Eros, for the case with LIDAR, and show that we have convergence from reasonable initial guesses.

9:20 **AAS 19-714** **OSIRIS-REx Orbit Determination Performance During the Navigation Campaign**

Jason Leonard, KinetX; Jeroen Geeraert, KinetX; Andrew French, University of Colorado ; Brian Page, KinetX Aerospace, Inc.; Peter Antreasian, KinetX Aerospace; Coralie Jackman, KinetX Aerospace; Michael Moreau, NASA Goddard Space Flight Center; Dante Lauretta, OSIRIS-REx; Daniel Wibben, KinetX, Inc.

The OSIRIS-REx mission Navigation Campaign consists of three sub phases: Approach, Preliminary Survey, and Orbital A. Approach was designed for initial characterization of Bennu while matching Bennu's velocity. Preliminary Survey provided the first estimate of Bennu's mass. This phase consisted of 5 target flybys with a close approach distance of about 7 km. Orbital A was a two-month long phase devoted to the Navigation team learning the close proximity operations dynamics and environment around Bennu and to transition from center-finding optical navigation (OpNavs) to landmark-based navigation. This paper will provide a detailed summary of the OD performance throughout the Navigation Campaign.

9:40 **AAS 19-708** **Dynamics of a non-rigid Orbital Siphon at a near-Earth asteroid**

Andrea Viale, University of Glasgow; Colin McInnes, University of Glasgow; Matteo Ceriotti, University of Glasgow

A bucket-conveyor mechanism is envisaged to deliver regolith from the surface of a rotating asteroid to a collection spacecraft, stationed above the synchronous orbit radius. The bucket-conveyor is designed as a non-rigid chain of payloads, linked by spring-dashpot connections, and is anchored to the asteroid on the lower-end and to the collection spacecraft on the upper-end. A net radial force is established on the chain due to the rotation of the asteroid (orbital siphon effect), which is exploited to provide a continuous flow of mass from the surface of the asteroid to the collection spacecraft. Several working scenarios are analysed.

10:00 **Morning Break**

Aug 14, 2019 Winslow Homer

Orbit Determination & Space Surveillance Tracking II

Chair: Craig McLaughlin, University of Kansas Aerospace Engineering, David Lujan, University of Colorado Boulder

8:00 **AAS 19-754** **High-fidelity drag coefficient models for orbit determination**
Vishal Ray, CU Boulder; Daniel Scheeres, University of Colorado Boulder

We present on our research on the development of Fourier series based drag coefficient models. We earlier proposed drag coefficient models based on Fourier expansion in the body frame to capture variations due to satellite orientation and in the orbit frame to capture periodic variations due to ambient parameters. In this work, we combine the two approaches to develop generic models that can capture a fully varying drag coefficient. The advantages of using these models in the presence of atmospheric density errors are demonstrated. Improvements in prediction capability are analyzed through simulations and processing of real data.

8:20 **AAS 19-716** **Application of Dual Number Theory to Statistical Orbital Determination**
Christopher Rabotin, Advanced Space LLC

In the field of statistical orbital determination, the state transition matrix, observations of a spacecraft and the mapping of these observations (the sensitivity matrix) to the estimate spacecraft state are fed into a Kalman filter. These matrices of partial derivatives are traditionally computed analytically, manually, or via symbolic manipulators. This paper demonstrates how the use of dual number theory eases these onuses. An implementation of this method has been demonstrated in a compiled programming language called Rust. Benchmarks show similar computation time performance between the analytical method and the hyper-dual method for computing the state transition matrix, and identical results.

8:40 **AAS 19-788** **Light Curve Inversion Observability Analysis**
Alex Friedman, Purdue University; Siwei Fan, Purdue University; Carolin Frueh, Purdue University

Resident space object (RSO) information beyond position and velocity is important for identification and accurate propagation. Measurements of most RSOs are non-resolved images, meaning details of object shape are not explicit in images. However, methods exist to recover shape information with light curve measurements from non-resolved images. The direct light curve inversion scheme consists of development of an Extended Gaussian Image followed by solving the Minkowski problem. Observability notions and methods are applied to the EGI generation process, and time between measurements is varied to study how measurements can be efficiently generated for use in the light curve inversion scheme.

9:00 AAS 19-704 NEW HORIZONS' ORBIT DETERMINATION PERFORMANCE THROUGHOUT THE EXTENDED MISSION TO ULTIMA THULE

Jeremy Bauman, KinetX Inc.; Derek Nelson, KinetX, Inc.; Frederic Pelletier, KinetX Inc.; Bobby G. Williams, KinetX, Inc.; Peter Wolff, KinetX Aerospace, Inc.; John Pelgrift, KinetX, Inc.; Dale Stanbridge, KinetX Aerospace; Joel Fischetti, KinetX Aerospace; Michael Salinas, KinetX Aerospace; Alan Stern, Southwest Research Institute; Leslie Young, Southwest Research Institute; Mark Holdridge, Johns Hopkins APL; Yanping Guo, JHUAPL; Gabe D. Rogers, The Johns Hopkins University Applied Physics Laboratory; H. A. Weaver, Johns Hopkins Univ. Applied Physics Lab; John Spencer, Southwest Research Institute; Marc Buie, Southwest Research Institute; Simon Porter, Southwest Research Institute; Erik Lessac-Chenen, KinetX Aerospace, Inc.; Cathy Olkin

KinetX Aerospace, Inc. has been the primary provider of navigaitonal services and products for New Horizions' primary and extended missions. This paper will focus on the key functions of the orbit determination process involving radio metric and optical measurements, the estimation of the Ultima Thule ephemeris, and the characterization of attitude control small forces acting on the spacecraft. A complete overview of the New Horizons extended mission is also presented in order to document the performance and results of the orbit determination and trajectory targeting maneuvers that enabled a successful flyby of Ultima Thule.

9:20 AAS 19-849 Sensor Configuration Trade Study for Navigation in Near Rectilinear Halo Orbits

Sehyun Yun, The University of Texas at Austin; Kirsten Tuggle, The University of Texas at Austin; Renato Zanetti, University of Texas at Austin; Christopher D'Souza, NASA - Johnson Space Center

NASA's Gateway is a NASA program planned to support a human space explo- ration and prove new technologies for deep space exploration. One of the Gateway requirements is to operate in the absence of communications with the Deep Space Network (DSN) for a period of at least 3 weeks. In this paper three types of onboard sensors (a camera for optical navigation, a GPS receiver, and X-ray navi- gation), are considered to enhance its autonomy and reduce the reliance on DSN. A trade study is conducted to explore alternatives on how to achieve autonomy and how to reduce DSN dependency

9:40 **AAS 19-636** **The effect of small forces on Juno Orbit Determination during the orbit phase**

Yu Takahashi, Jet Propulsion Laboratory; Paul Stumpf, Jet Propulsion Laboratory; Brian Rush, NASA / Caltech JPL; Nicholas Bradley, Jet Propulsion Laboratory; John Bordi, NASA / Caltech JPL

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During the orbit phase, the precession turns, also known as small forces, are one of the key parameters to estimate for the Juno orbit determination team. It is the purpose of this paper to evaluate different error sources, particularly the Jupiter barycenter ephemeris, and analyze the effect of the small force in terms of the performance between the prediction and reconstruction solution deliveries used for the maneuver design.

10:00 **Morning Break**

10:20 **AAS 19-689** **Independent Navigation Team Orbit Estimation of 2014MU69 for New Horizons' Kuiper Belt Object Flyby**

Dylan Boone, Jet Propulsion Laboratory / California Institute of Technology; Shyam Bhaskaran, Jet Propulsion Laboratory; Gerhard Kruizinga, NASA / Caltech JPL; William Owen, Jet Propulsion Laboratory; Ed Riedel, NASA Jet Propulsion Laboratory; Jeffrey Stuart, Jet Propulsion Laboratory; Declan Mages, NASA / Caltech JPL; Dianna Velez, NASA / Caltech JPL

The New Horizons spacecraft became the first to successfully flyby a Kuiper Belt Object, 2014MU69, nicknamed Ultima Thule (UT), on January 1, 2019 . Doing so required the creation of an accurate ground-based *a priori* ephemeris using Hubble image data and occultation data and subsequently updating this ephemeris prior to the flyby using optical navigation images taken with the onboard LORRI camera. This paper details the JPL Independent Navigation team’s experience refining UT’s ephemeris through optical navigation and how imaging of UT from the spacecraft improved the ground-based orbit solution by reducing the *a priori* covariance ellipsoid.

10:40 **AAS 19-752** **Implementing an Idan Speyer Cauchy Drag Estimator**

Craig McLaughlin, University of Kansas Aerospace Engineering; Micaela Crispin, University of Kansas ; Frank Bonet, University of Kansas

Recent work shows that drag related parameters can better be described by a Cauchy distribution than a Gaussian. For this reason, an Idan Speyer Cauchy drag estimator is nested within an extended Kalman filter orbit determination process. The estimator is tested along the CHAMP satellite orbit and the drag acceleration measurements are calculated using CHAMP accelerometer-derived densities. In addition, the distribution of the density residuals, defined as the difference between the accelerometer-derived density and the NRLMSISE-00 density, is examined to see if it better matches a Cauchy or Gaussian distribution.

11:00 **AAS 19-781** **Analysis of Relative Merits of Unscented and Extended Kalman Filters in Orbit Determination**

James Woodburn, Analytical Graphics, Inc.; Vincent Coppola, Analytical Graphics, Inc.

The Extended Kalman Filter (EKF) and Unscented Kalman Filter (UKF) are compared in application to a variety of practical orbit determination scenarios. As reported advantages of the UKF are based on the incorporation of non-linear terms and recognizing filtering algorithms as recursive machines of time and measurement updates, each type of update is independently examined to detect the existence and consequence of higher order effects. The possibility of a EKF/UKF hybrid filter is explored where beneficial aspects of each algorithm are retained. The included problem set is used to develop guidelines to indicate when a particular filtering algorithm may preferred.

11:20 **AAS 19-885** **Automated Navigation Analysis for the Lucy Mission**

Jeremy Knittel, KinetX Aerospace, Inc.; Dale Stanbridge, KinetX Aerospace

The Lucy interplanetary trajectory presents a computationally challenging numerical optimization problem. The number of small body encounters presents an onerous navigation analysis process. Automating the trajectory targeting, data simulation and orbit determination process has increased the overall robustness of the navigation plan. These new techniques have allowed rapid trade studies to be performed comparing different navigation concepts of operations. This work will highlight the orbit determination process for Lucy, the methodology of automating much of the navigation analysis, and present results for some preliminary trade studies performed.

11:40 **AAS 19-890** **Orbit determination and tests of general relativity in the cruise phase of BepiColombo**

Luciano Iess, Sapienza University of Rome; Ivan Di Stefano, Sapienza University of Rome; Paolo Cappuccio, Sapienza University of Rome; Gael Cascioli, Sapienza University of Rome

The ESA spacecraft BepiColombo will carry out accurate tests of relativistic gravity during cruise and while in orbit around Mercury. The onboard microwave instrumentation enables very precise range and range rate measurements even during superior solar conjunctions, offering the opportunity to improve the classical test of time delay and frequency shift of radio signals. We analyze the dynamical noise introduced by fluctuations in the solar irradiance and show by means of numerical simulations that suitable stochastic models can still provide an estimate of the relativistic time delay with improved accuracy over previous tests.

Aug 14, 2019 Hawthorne

Special Session: Artificial Intelligence in Astrodynamics I - Machine Learning

Chair: Simone D'Amico, Stanford University, Islam Hussein, Applied Defense Solutions

8:00 **AAS 19-776** **Uncertainty Characterization and Surrogate Modeling for Angles Only Initial Orbit Determination**

David Schwab, The Pennsylvania State University; Puneet Singla, Pennsylvania State University; JOSEPH RAQUEPAS, Air Force Research Laboratory

Initial orbit determination may be used to initialize object tracking or even associate observations with a tracked satellite, but only if uncertainty information exists for the approximated orbit. While classical initial orbit determination algorithms only provide a point solution, uncertainty information may be inferred using Monte Carlo or deterministic sampling techniques. Along with uncertainty characterization, two statistical learning techniques are tested in their ability to approximate the orbit determination mapping: 1) a polynomial approximation built from the statistical moments in the state space, and 2) Gaussian Process Regression.

8:20 **AAS 19-700** **Deep Imitation Learning and Clustering in Astrodynamics**

Roberto Furfaro, The University of Arizona; RICHARD LINARES, Massachusetts Institute of Technology; Kristofer Drozd, University of Arizona; Brian Gaudet, The University of Arizona; Andrea Scorsoglio, University of Arizona

This paper explore the use of meta-learning frameworks both for supervised and unsupervised methods for structure understanding in dynamical systems typically arising in astrodynamics.

8:40 **AAS 19-813** **Deep Learning Applications to Astrodynamics Problems**

Jordan Murphy, University of Colorado; Daniel Scheeres, University of Colorado Boulder

This paper investigates the ability of deep learning to characterize and predict particle dynamics in complex gravitational fields by using a number of advanced machine learning techniques. Both fully integrated models and sub-problem approximations are used to create the training sets. From these sets, predictions of the state space of the trajectory are made into the future. The accuracy and computational complexity of these techniques are compared with traditional methods.

9:00 **AAS 19-840** **Towards Robust Learning-Based Pose Estimation of Noncooperative Spacecraft**

Tae Ha Park, Stanford University; Sumant Sharma, Stanford University; Simone D'Amico, Stanford University

This work presents a novel Convolutional Neural Network (CNN) architecture that has scored a fourth place inthe recent Pose Estimation Challenge hosted by Stanford's Space Rendezvous Laboratory (SLAB) and the Advanced Concepts Team (ACT) of the European Space Agency (ESA). This work also introduces texture randomization as part of the training procedure of the CNN. By randomizing the texture of the spacecraft in the synthetic images at the training stage, the CNN can generalize to spaceborne imagery without additional training.

9:20 **AAS 19-873** **Gaussian Process models for preliminary low-thrust trajectory optimization**

Kevin Cowan, Delft University of Technology; Lieve Bouwman, Delft University of Technology; Yuxin Liu, Delft University of Technology

Low-thrust trajectories can benefit the search for propellant-optimal trajectories, but increases in modeling complexity and computational load remain a challenge for efficient mission design and optimization.

In this paper, a robust procedure for developing Gaussian Process regression and classification models is proposed for computationally efficient optimization based on exponential sinusoid shaping.

Using the developed procedure, three Gaussian Process models are constructed and tested for performance based on the mean absolute percentage error and processing time. The computational burden is significantly reduced while comparable accuracy is maintained versus traditional optimization techniques with shape-based transfers to Mars.

9:40 **AAS 19-830** **Covariance Fusion Method of Gaussian Processes Covariance and Orbital Prediction Uncertainty**

Hao Peng, Rutgers, The State University of New Jersey; Xiaoli Bai, Rutgers

The previously proposed machine learning (ML) approach could recover the relationship between orbit prediction errors and particular historical data. The trained ML models could then be used to modify future orbit predictions. Many Bayesian inference techniques, such the Gaussian Processes (GP) used in this paper, could not only generate a correction, but also the covariance information about this correction. This paper will introduce a new approach based on extended Kalman filter (EKF) to incorporate the GP covariance information, which is expected to generate more reliable corrections to future orbit predictions.

10:00 Morning Break

10:20 AAS 19-697 Calibration of atmospheric density model based on Gaussian process

Tianyu Gao, Rutgers, The State University of New Jersey; Hao Peng, Rutgers, The State University of New Jersey; Xiaoli Bai, Rutgers

To accurately predict the trajectories of space objects at low attitude, the atmospheric density is most essential in the estimation of the drag force. This work presents a novel method to estimate atmospheric density, with goal to reduce the error of density estimated along the orbit of a satellite using existing methods. The preliminary simulations demonstrate the benefit, and potential performance advancement for the density prediction using the proposed approach.

10:40 AAS 19-784 Adaptive Online Learning Strategy for Post-capture Attitude Takeover Control of Noncooperative Space Target

Yueyong Lyu, Harbin Institute of Technology; Yuhan Liu, Harbin Institute of Technology; Sun Zhaowei; Guangfu Ma, Harbin Institute of Technology

This paper investigates the problem of the post-capture attitude takeover control for partial constrained combined spacecraft, subject to the unknown dynamics of the noncooperative target. An online learning control strategy is developed for post-capture attitude stabilization and maneuvering based on adaptive dynamic programming. The real-time inertia identification is avoided, while only I/O data is utilized to generate the control strategy. It is capable to adjust its parameters online over time under various working conditions, which is very suitable for the combined spacecraft with complex time-varying dynamics. Theoretical analysis and simulations are exhibited to validate the effectiveness of the proposed strategy.

11:00 AAS 19-773 Neural Network Based Optimal Control: Resilience to Missed Thrust Events for Long Duration Transfers

Ari Rubinsztejn, University of Alabama; Rohan Sood, University of Alabama; Frank Laipert, Jet Propulsion Laboratory

A growing number of spacecraft are continuing to adopt new and more efficient forms of in-space propulsion. These high-efficiency propulsion techniques do come with downsides, chief among them is their low-thrust capabilities. This requires them to thrust continuously for long periods of time and makes these spacecraft susceptible to missed thrust events. This paper demonstrates how neural networks can autonomously

correct for missed thrust events during an example low-thrust long duration transfer to a circular trajectory. Methods for improving the response of neural networks to missed thrust events are then presented and investigated.

Aug 14, 2019 Eastland Ball Room

Trajectory Design & Optimization IV

Chair: Jennifer Hudson, Western Michigan University

8:00 **AAS 19-688** **Efficient Computation of Optimal Low Thrust Perturbed Orbit Transfers with Shadow Constraints**

Robyn Woollands, Jet Propulsion Laboratory; Ehsan Taheri, Auburn University

We have developed a method for solving low-thrust, fuel-optimal, orbit transfer problems considering a highly-nonlinear gravity model and thrusting constraints due to shadows. The algorithm is formulated via indirect optimization which leads to a two-point boundary value problem. We make use of a hyperbolic tangent smoothing law for performing continuation on the thrust magnitude and shadow regions, to reduce the sharpness of on/off thrust switches and aid in numerical convergence. The two-point boundary value problem is solved using the method of particular solutions and Picard-Chebyshev numerical integration. The algorithm is tested for a multi-revolution orbit transfer from GTO to GEO.

8:20 **AAS 19-614** **Refining Lucy Mission Delta-V during Spacecraft Design using Trajectory Optimization within High-Fidelity Monte Carlo Maneuver Analysis**

Jim McAdams, KinetX, Inc.; Kenneth Williams, KinetX Aerospace, Inc.; Jacob Englander, NASA Goddard Space Flight Center; Donald Ellison, NASA Goddard Space Flight Center; Jeremy Knittel, KinetX Aerospace, Inc.; Dale Stanbridge, KinetX Aerospace; Brian Sutter, Lockheed-Martin; Kevin Berry, NASA Goddard Space Flight Center

Recent advances linking medium-fidelity global trajectory optimization and high-fidelity trajectory propagation/maneuver design software with Monte Carlo maneuver analysis and parallel processing have enabled more realistic statistical delta-V estimation well before launch. Completing this high-confidence, refined statistical maneuver analysis occurred early enough to release excess delta-V margin for increased dry mass margin for the Lucy Jupiter Trojan flyby mission. By 3.4 years before launch, 16 of 34 TCMs had 1000 re-optimized trajectory design samples, yielding tens of m/s lower 99%-probability delta-V versus targeting maneuvers to one optimal trajectory. By 1.1 year later, re-optimizing all maneuvers and flybys will further lower delta-V.

8:40 **AAS 19-924** **Novel Chebyshev Collocation Method for Trajectory Optimization**

Tyler Doogan, Texas A&M University; Manoranjan Majji, Texas A&M University, College Station

This new Chebyshev collocation method approximates the dynamics instead of the states. By doing this we are able to take an exact integral of this approximation using unique properties of the Chebyshev polynomials. The advantages of using this method are shown as compared to similar pseudospectral methods.

9:00 **AAS 19-824** **Revisiting Trajectory Design with STK Astrogator, Part 1**

Cody Short, Analytical Graphics, Inc.; Pradipto Ghosh, Analytical Graphics, Inc.; Austin Claybrook, Analytical Graphics, Inc.

As orbital regimes become more crowded and attainable from an expanding industry, new challenges arise. Research efforts to better understand previously unexploited strategies and drive innovation in the face of new constraints continue to increase. It is not uncommon for trajectory designers to spend much of their time creating tools for their virtual work space. The Systems Tool Kit (STK) Astrogator module from Analytical Graphics, Inc. (AGI) is one such tool intended to improve the trajectory design process, both for the designer and for the design. Astrogator's evolving development is the subject of this paper.

9:20 **AAS 19-705** **Libration Orbit Eclipse Avoidance Maneuver Study for the James Webber Space Telescope Mission**

Wayne Yu, NASA GSFC; Karen Richon, NASA GSFC

Mission analysis of libration orbit trajectories at the L2 Sun-Earth/Moon barycenter system typically include predictions of Lunar and Earth eclipses during the mission lifetime. The NASA James Webb Space Telescope (JWST) operational orbit, by design, avoids these eclipses by pruning its launch window. In an off-nominal scenario where an eclipse is predicted, a maneuver strategy is needed. In this paper, trade studies are examined for JWST that characterize the burn magnitude, location, and epochs of multiple maneuver plans to avoid an eclipse. The results enable analysts to explore the space of feasible maneuver strategies during routine operations.

9:40 **AAS 19-611** **Low thrust variable specific impulse fuel-optimal transfers between planetary parking orbits**

Padmanabha Prasanna Simha, California Institute of Technology; Ramanan R V, Indian Institute of Space Science and Technology

Optimizing low thrust transfers between planetary parking orbits is a complex problem due to the large number of revolutions that are required during planetary escape and capture apart from a heliocentric phase. Here, a new solution method has been developed and presented to obtain near-optimal transfers using Pontryagin's principle and the KKT conditions to handle control constraints. The resulting two-point boundary value problem is solved using differential evolution, a search based global optimization technique. Near-optimal transfers have been obtained here with thrusters having a much narrower range of operating specific impulses in comparison to the results available in literature.

10:00 Morning Break

10:20 AAS 19-750 OPTIMIZATION IN SPACE-BASED PURSUIT-EVASION GAMES THROUGH COMPETITIVE COEVOLUTION

Jason Reiter, Penn State ARGoPS; David B. Spencer, Pennsylvania State University

Optimization in space-based pursuit-evasion games is often computationally cost prohibitive given the size of the state and action spaces available to both players. Competitive coevolution can be used to augment the optimization process in a manner that results in dynamic search spaces. In competitive coevolution, the two players compete directly with each other and reciprocally drive one another to increasing levels of performance and complexity. This is accomplished by gradually increasing the size and complexity of the strategies available to both players. Using coevolution provides significant computational cost savings compared to traditional optimization methods while ensuring a globally optimal result.

10:40 AAS 19-865 ANALYSIS OF A CONSTRAINED OPTIMAL MULTIPLE-PHASE LANDING TRAJECTORY FOR A SMALL ROBOTIC LUNAR LANDER

J.P. Carrico; Alisa Hawkins, Google/Skybox; Jae-ik Park, Korea Aerospace Research Institute; Dong-Young Rew, Korea Aerospace Research Institute

Korea has plans for launching a lunar lander using its own launch vehicle after the completion of Korea’s first lunar orbiter named Korea Pathfinder Lunar Orbiter (KPLO). This paper details how the constrained optimal multiple-phase landing trajectory of a small robotic lunar lander was analyzed for the second phase of Korea lunar exploration program. For this effort, a preliminary trajectory in GPOPS-II was migrated into AGI STK/Astrogator and further constraints appliued and optimized over using SNOPT (Sparse Nonlinear OPTimizer). Lastly, this descent trajectory planning model, including the trajectory optimization component, was integrated into a forward propagated, high fidelity end-to-end trajectory.

11:00 AAS 19-878 Selecting Planning Horizon Length for Sequential Low-Thrust Orbit-Raising Optimization Problem

Pardhasai Chadalavada, Wichita State University; Atri Dutta, Wichita State University

In this paper, we revisit the low-thrust multi-revolution orbit-raising problem formulated as a sequence of optimal control sub-problems, each of which computes the trajectory over a planning horizon. Each sub-problem solves an unconstrained optimization problem described in terms of dynamical coordinates, by minimizing a convex combination of three components reflecting the deviation of the maneuvering spacecraft from the geosynchronous equatorial orbit. This paper explores the impact of planning horizon time-length on the optimality gap of the computed solutions, by considering minimum-time solutions as the reference. Numerical results are presented by considering transfers starting from geosynchronous transfer orbits, planar and non-planar.

Aug 14, 2019 Rines A

AAS Committee Lunch

Aug 14, 2019 Winslow Homer

Attitude Dynamics & Control I

Chair: Atri Dutta, Wichita State University

13:30 **AAS 19-777** **ICESat-2 Precision Pointing Determination**

Sungkoo Bae, The University of Texas at Austin; Benjamin Helgeson, The University of Texas at Austin; Michael James, The University of Texas at Austin; Jonathan Sipps, The University of Texas at Austin

The Precision Pointing Determination (PPD) is a crucial component of the ICESat-2 mission. It must accurately determine the location of where the laser hit on the surface. Due to serious performance issues in the main star tracker after the ICESat-2 launch in Sep. 2018, the actual PPD is conducted by a contingency plan. Based on various assessments, the current PPD successfully meets the required accuracy goal. This paper describes ICESat-2 PPD at the University of Texas at Austin: preparation, adaptation, performance, and evaluation. It also discusses our ongoing efforts to improve the performance of the original plan.

13:50 **AAS 19-927** **Magnetorquer-Only Attitude Control of Small Satellites using Trajectory Optimization**

Andrew Gatherer, Stanford University; Zachary Manchester, Stanford University

Due to the ever-increasing scope of small satellite missions, there is now significant demand for precise attitude determination and control capabilities onboard CubeSats. Interactions between magnetic torque coils and the Earth's magnetic field have been used for decades onboard satellites to offload momentum from reaction wheels and control-moment gyroscopes. However, magnetorquers are inherently underactuated, and mechanical actuators like reaction wheels are often prohibitively expensive in terms of mass, volume, power, and cost for CubeSat missions. This paper presents a magnetorquer-only attitude control technique that utilizes trajectory optimization to circumvent the under-actuated nature of satellite magnetic field interactions.

14:10 **AAS 19-844** **Reaction Wheel Friction Analysis for the Fermi Spacecraft**

Benjamin Ellis, KBRwyle, Inc.; Russell DeHart, KBRwyle

The Fermi Gamma-ray Space Telescope is a three-axis stabilized spacecraft in Low Earth Orbit. Responding to concerns about reaction wheel health raised by drag torque trending, this study calculates Coulomb and viscous friction coefficients from Fermi’s reaction wheel telemetry. We describe the method used including bounded-error undithering and Theil-Sen regression. Results taken from sample long time spans at similar beta angle ranges indicate friction has been growing slowly over the spacecraft's time on orbit.

14:30 **AAS 19-607** **Modelling and Simulation of the ADCS Subsystem for JY1-SAT**
Ahmad Fares, Crown Prince Foundation; Ahmad Bani Younes, San Diego State University

In this paper, modelling and simulation of the attitude control subsystem for JY1Sat is presented. Three
orthogonal magnetorquers are used and detumbling is achieved by two axes actuation. B-dot controller is
used as the control law and three axes magnetometer is used to provide Earth magnetic field measurements.
Performance of the control law with disturbance torques is verified. International Geomagnetic Reference
Field model is used to obtain the magnetic measurements for simulation purposes and J6 perturbation orbit
propagator is built and verified. A case study on the attitude regulation using Modified Rodrigues Parameters
and Lyapunov control functions is investigated.

14:50 **AAS 19-615** **Performance Improvements for the Lunar Reconnaissance Orbiter Gyroless Extended Kalman Filter**
Julie Halverson, NASA GSFC; Philip Calhoun; Oscar Hsu

In late 2017, the laser intensity monitor current began to decline on the Lunar Reconnaissance Orbiter miniature inertial measurement unit (MIMU). The MIMU was powered off in March 2018 and has only been used during critical operations. Slews were suspended, and the extended Kalman filter (EKF) was disabled. A complementary filter was uploaded to the spacecraft in December 2018. The EKF was enabled, using the complementary filter rate in place of the MIMU and slews are now being performed. This paper presents an overview of the complementary filter rate estimation and EKF changes, fault detection updates, and inflight performance improvements.

15:10 **AAS 19-654** **QuateRA: The Quaternion Regression Algorithm**
Marcelino Mendes de Almeida, The University of Texas at Austin; Maruthi R. Akella, The University of Texas at Austin; Renato Zanetti, University of Texas at Austin; Daniele Mortari, Texas A&M University

This work proposes a batch solution to the problem of estimating fixed angular velocity using orientation measurements. Given constant angular velocity, the orientation quaternion belongs to a constant plane of rotation as time evolves. Motivated by this fundamental property, we are able to determine the angular velocity's direction by estimating the quaternion plane of rotation. The angular velocity magnitude is estimated by projecting the measured quaternions onto the estimated plane of rotation, and then computing the least squares evolution of the quaternion angle in the plane. We perform a Monte Carlo analysis of the proposed algorithm, validating our method.

15:30 Afternoon Break

15:50 AAS 19-735 SINGULARITY-FREE EXTRACTION OF A DUAL QUATERNION FROM FEATURE-BASED REPRESENTATION OF MOTION

Daniel Condurache, Technical University of Iasi

Recently, orthogonal dual tensors and dual quaternion proved to be a complete tool for computing rigid body displacement and motion parameters. The present research is focused on developing new methods for recovering kinematic data when the state of features attached to a body during a rigid displacement is available. The proof of concept is sustained by computational solutions both for the singularity-free extraction of a dual quaternion from feature-based representation of motion and for the recovery algorithms of the dual quaternion and the dual Rodrigues vector.

16:10 AAS 19-609 Recursive and Non-dimensional Star-Identification

Carl Leake, Texas A&M University; Daniele Mortari, Texas A&M University

This paper describes two new algorithms to identify the stars observed by a wide field-of-view star tracker. The first algorithm, called recursive, is proposed for performing the star identification process when the task must be executed in the fastest possible way; for example, during rapid attitude maneuvers, when the attitude information must be provided to the control system at the highest rate. The second algorithm, called non-dimensional, is proposed when both the recursive Star-ID algorithm and the lost-in-space algorithm (LISA)--used to initialize the recursive algorithm--fail because the values of the star tracker parameters go beyond the nominal operational range.

16:30 AAS 19-620 NEW CONTROL SCHEMES AND FLIGHT RESULTS OF WORLD’S SMALLEST SS-520 NO.5 FOR MICRO-SATELLITE

Hirohito Ohtsuka, IHI Aerospace Co.,Ltd.; Yasuhiro Morita, Japan Aerospace Exploration Agency; Naruhisa Sano, IHI Aerospace Co.,Ltd; Takahiro Ito, Japan Aerospace Eploration Agency

ISAS/JAXA has successfully launched the micro-satellite “TRICOM-1R” by the world’s smallest orbit rocket ”SS-520 No.5” from Uchinoura Space Center on February 3rd in 2018. ISAS modified the existing sounding rocket SS-520 addind a small 3rd-stage solid-motor and the attitude control system.It flies spinning for the attitude stabilization in the flight. Therefore, we devised the rhumb-line control system with a new scheme. This rhumb-line system has the high-performance functions; the high-preciseness, the high-maneuver rate and the suppression of the unnecessary nutation angle generated at the RCS injection. This paper reports the development of the G&C system and the flight results.

Aug 14, 2019 Hawthorne

Dynamical Systems Theory II & Asteroid and Non-Earth Orbiting Missions III

Chair: Siamak Hesar, Blue Canyon Technologies

13:30 **AAS 19-723** **Frequency Structure of the NRHO Family in the Earth-Moon System**
David Lujan, University of Colorado Boulder; Daniel Scheeres, University of Colorado Boulder

Center manifold frequencies are mapped out for the Near Rectilinear Halo Orbit (NRHO) family in the Earth-Moon system, along with their continuation to nonlinear quasi-periodic orbits. The motivation is to develop a map of the dynamics of relative motion on and about NRHOs, which is essential to understand proximity motion and rendezvous in this class of orbits. Extending our analysis to nonlinear quasi-periodic orbits, which are the most prevalent type of regular behavior in the circular restricted three-body problem, enables more accurate planning. A significant challenge in this study is the representation of the quasi-periodic orbits and their frequencies.

13:50 **AAS 19-825** **Observability and Estimability Analysis of the Orbit Problem**
Alex Friedman, Purdue University; Carolin Frueh, Purdue University

With easier access to space, the challenge of tracking the resident space object (RSO) population becomes even more difficult. The connection of observability and the Kalman filter is explored for facing this RSO tracking challenge. Often, observability is computed without state and measurement uncertainties, but many stochastic observability methods have been developed. In addition, methods for evaluating estimation performance, called estimability, are useful to study alongside observability. A review of stochastic observability and estimability methods for the orbit problem is conducted. A consider filter approach utilizing specific observability and estimability methods is developed for improved RSO propagation and identification.

14:10 **AAS 19-724** **Transfer Trajectory Options for Servicing Sun-Earth-Moon Libration Point Missions**
David Folta, NASA Goddard Space Flight Center; Cassandra Webster, NASA Goddard Space Flight Center

Future missions to the Sun-Earth Libration L_1 and L_2 regions will require scheduled servicing to maintain hardware and replenish consumables. While there have been statements made by various NASA programs regarding servicing of vehicles at these locations or in Cis-lunar space, a true feasibility transfer study has not been extensively investigated in an operational fashion. This investigation uses dynamical systems and operational models to design transfer trajectories between the Sun-Earth Libration region (Lyapunov, Lissajous, and Quasi-halo) and the Earth-Moon vicinity (Distant Retrograde, Quasi-Halo, Lissajous, and Near Rectilinear Halo Orbits). We address the cost of transfers between each pair of locations.

14:30 **AAS 19-740** **Survey of Ballistic Lunar Transfers to Near Rectilinear Halo Orbit**
Nathan Parrish, Advanced Space, LLC; Ethan Kayser, Advanced Space, LLC; Shreya Udupa, Advanced Space, LLC; Jeff Parker, Advanced Space, LLC; Bradley Cheetham, Advanced Space; Diane Davis, a.i. solutions, Inc.

14:50 **AAS 19-681** **The Long-Term Forecast of Station View Periods for Elliptical Orbits**
Andrew Graven, Cornell University; Martin Wen-Yu Lo, Jet Propulsion Laboratory

In a previous paper, using ergodic theory, Dr. Martin Lo derived a simple definite integral that provided an estimate of the view periods of ground stations to satellites. This assumes the satellites are in circular orbits with non-repeating ground tracks under linear J2 perturbations. The novel feature is that this is done without the propagation of the trajectory by employing ergodic theory. This accelerated the telecommunications mission design and analysis by several orders of magnitude and greatly simplified the process. In this paper, we extend the view period integral to elliptical orbits.

15:10 **AAS 19-808** **Dynamical Structures Nearby NRHOs with Applications in Cislunar Space**
Emily Zimovan-Spreen, Purdue University; Kathleen C. Howell, Purdue University

The development of a methodology to move through cislunar space along fundamental dynamical paths is relevant to NASA's cislunar transportation network goals. To enable an informed design approach for transfer trajectories departing from or arriving at a near rectilinear halo orbit (NRHO), higher-period orbits that bifurcate from the NRHO region of the halo orbit family are combined with other known structures, such as Lagrange point and resonant orbits, in the Earth-Moon neighborhood. As a result of this design strategy, novel impulsive transfer options between NRHOs and distant retrograde orbits that possess predictable geometries are constructed.

15:30 **Afternoon Break**

15:50 **AAS 19-871** **OPTICAL NAVIGATION FOR NEW HORIZONS' FLYBY OF KUIPER BELT OBJECT (486958) 2014 MU69**
Derek Nelson, KinetX, Inc.; Erik Lessac-Chenen, KinetX Aerospace, Inc.; John

Pelgrift, KinetX, Inc.; Coralie Adam, KinetX, Inc.; Frederic Pelletier, KinetX Inc.; Jeremy Bauman, KinetX inc.; Dale Stanbridge, KinetX Aerospace; John Spencer, Southwest Research Institute; Simon Porter, Southwest Research Institute; Marc Buie, Southwest Research Institute; Mark Holdridge, Johns Hopkins APL; H. A. Weaver, Johns Hopkins Univ. Applied Physics Lab; Cathy Olkin; Alan Stern, Southwest Research Institute

Due to relatively large a priori spacecraft to target uncertainties, optical navigation has played an integral role in the orbit determination and navigation of NASA's New Horizons spacecraft to its most recent target, Kuiper Belt Object (486958) 2014 MU_{69}. Key functions of the New Horizons optical navigation process include observation planning, calibration and processing, attitude determination, planetary modeling, star and target centroiding, and other astrometric reduction techniques. These key functions as well as the approach and trajectory reconstruction optical navigation results from New Horizons' flyby of 2014 MU_{69} will be explored.

16:10 **AAS 19-677** **OSIRIS-REX FROZEN ORBIT DESIGN AND FLIGHT EXPERIENCE**

Daniel Wibben, KinetX, Inc.; Andrew Levine, KinetX, Inc.; Samantha Rieger; Jim McAdams, KinetX, Inc.; Peter Antreasian, KinetX Aerospace; Jason Leonard, KinetX; Michael Moreau, NASA Goddard Space Flight Center; Dante Lauretta, OSIRIS-REx

The OSIRIS-REx mission successfully captured in a closed orbit around target asteroid Bennu for the first time on December 31, 2018. Due to the extremely low gravity of the asteroid, a specific orbit design was necessary to balance the perturbations provided from solar radiation pressure in order maintain spacecraft safety, meet mission requirements, and demonstrate stability over a propagation period of several months. This paper describes the design for OSIRIS-REx's record-setting orbit and the as-flown performance of the spacecraft while it remained in orbit for two months without need for orbit maintenance.

16:30 **AAS 19-656** **Autonomous Architectures for Small Body Exploration**

Daniel Scheeres, University of Colorado Boulder; Jay McMahon, University of Colorado Boulder

Architectures for the autonomous exploration of a small body using a rendezvous spacecraft are studied. The approaches are inspired by the OSIRIS-REx mission, which will focus on placing the spacecraft into a stable orbit, and the Hayabusa2 mission, which will focus on controlling the spacecraft in a quasi-hovering state for an extended period of time. These different architectures will be analyzed in terms of necessary navigation measurements and model estimation requirements, robustness of operations,

and other criterion. The goal is to identify the relative advantages of each approach and to formulate appropriate mission goals based on the architecture used.

16:50 AAS 19-887 Spacecraft Trajectory Tracking and Parameter Estimation in the Presence of a Splitting Contact Binary Asteroid

Tiago Silva, University of Illinois at Urbana-Champaign; Koki Ho, University of Illinois, Urbana-Champaign; Jean-Baptiste Bouvier, University of Illinois; Kathleen Xu, University of Illinois; Masatoshi Hirabayashi, Auburn University

Increasing interest in asteroid mining and in-situ resource utilization will lead to an increase in asteroid surface operations. The composition of asteroids is often unknown and potentially unstable, many of which are bound together predominantly by gravitational forces. Surface operations such as mining may significantly alter the asteroid's structure or, in the case of contact binary asteroids, cause the asteroid to split. The coupled problem of estimating unknown parameters of a newly-formed binary system and controlling a spacecraft's trajectory in the system's vicinity is investigated. An indirect adaptive control scheme is utilized to simultaneously and accurately meet both objectives.

Aug 14, 2019 Longfellow

Orbital Debris and Space Environment

Chair: Juan Arrieta, Nabla Zero Labs

13:30 **AAS 19-616** **Spaceflight Hazards of Escape-Velocity-Domain Impact Ejecta in the CR3BP**

Matthew Wittal, National Aeronautics and Space Administration; Shaun Butts, National Aeronautics and Space Administration

As a consequence of planned/proposed human lunar activity, the long-term effects of debris and ejecta resulting from large-body (_body_gt;1000$ kg) impacts and general activity on the lunar surface is investigated. The escape-velocity-domain ejecta behavior is characterized in terms of destination, duration in lunar orbit, and total displaced mass in orbit.

13:50 **AAS 19-707** **Real-Time Neutral Density Estimation Via Two-Line-Element Data Fusion In A Quasi-Physical Thermosphere Model**

David Gondelach, Massachusetts Institute of Technology; RICHARD LINARES, Massachusetts Institute of Technology

Quasi-physical dynamic reduced-order models of the atmosphere have been developed recently and allow accurate and efficient neutral density forecasting. In this paper, we demonstrate the real-time estimation of the neutral density though data assimilation of two-line element (TLE) orbital data in a quasi-physical dynamical model. The accuracy of the density model calibration and forecasting is then assessed by comparing orbit predictions using the density forecasts with accurate GPS position data of known satellites. The developed tool allows density forecasting for space operators that don’t have access to highly-accurate orbital data and currently employ empirical models for density calculations.

14:10 **AAS 19-730** **Multiple Small-Satellite Salvage Mission Sequence Planning for Debris Mitigation**

Guanwei He, Pennsylvania State University; Robert Melton, Pennsylvania State University

This paper presents a new and efficient method, using a heuristic optimization algorithm, for computing impulsive maneuver transfers to capture multiple dysfunctional satellites or debris objects in different orbits and bring them back to a space station. An improved Genetic Algorithm (GA) is applied to determine the optimal visiting sequence of the target satellites by analyzing the propellant consumption of the

servicing spacecraft to transport all the satellites to the space station. The transfer between two targets is represented by a relatively simple model that contains only the planar changes and orbital maneuvers.

14:30 AAS 19-889 Characterizing the India ASAT debris evolution using diverse, complementary tools

Daniel L. Oltrogge, Analytical Graphics, Inc; T.S. Kelso; Timothy Carrico, Analytical Graphics, Inc.

The recent India ASAT intercept is a poignant reminder of the need for tools to model a kinetic engagement, build representative scenarios of the resulting debris cloud, and further characterize the likelihood of a fragment being present anywhere in three-dimensional space as a function of time. In this paper we examine a sequence of modeling tools for end-to-end collision, explosion and kinetic ASAT intercept fragmentation cloud modeling, including additional derived data such as an assessment of the "top 25" active satellites placed at highest temporal risk of secondary collision with fragments, as well as statistics on orbits and their lifetimes.

14:50 AAS 19-841 Tracking Multiple Maneuvering Satellites Using a Generalized Labeled Multi-Bernoulli Filter

Nicholas Ravago, The University of Texas at Austin; Brandon Jones, University of Texas at Austin

Companies are planning to deploy large constellations of hundreds to thousands of maneuver-capable spacecraft for various purposes. Current methods applied in space object tracking represent maneuvering object dynamics using a fixed set of possible dynamical modes, which can be suboptimal and computationally inefficient. We propose the use of a data-adaptive variable structure approach that designs possible dynamical models based on observation data. This method is integrated into a Generalized Labeled Multi-Bernoulli Filter to allow multiple maneuvering objects to be tracked simultaneously. The resulting filter is tested on a population of maneuvering objects in geosynchronous orbit.

15:10 AAS 19-910 Collision Probability for Parallelogram Cross Sections

Ken Chan, Chan Aerospace Consulting

A closed-form analytical expression is obtained for computing the collision probability when the cross section is a parallelogram. It is based on the conversion of a parallelogram first to a rectangle and then into a circle, each with the same area and the same centroid. The results so obtained agree to five or six significant figures with detailed computations using realistic values of the covariance and miss distance of

spacecraft encounters. The applications are for use with solar panels, solar sails and CubeSats faces when their collision cross sections are general parallelograms when viewed obliquely.

15:30 Afternoon Break

15:50 AAS 19-911 Collision Probability for General Polygonal Cross Sections
Ken Chan, Chan Aerospace Consulting

This paper deals with the formulation of analytical expressions for computing the collision probability when the cross section is a polygon of any shape. It is based fundamentally on the conversion of a triangle into its equivalent rectangle and subsequent circle, each with the same area and the same centroid. Since any polygon can be decomposed into a network of triangles, the totality of collision probabilities obtained from all the triangles will yield the collision probability of the polygonal cross section. The intended application is for ambitiously modeling the actual collision cross section of an entire spacecraft with space debris.

16:10 AAS 19-942 Evaluation of the 27 March 2019 Indian ASAT Demonstration
Andrew Abraham, The Aerospace Corporation

On 27 March 2019 India announced the successful execution of a Direct Ascent ASAT demonstration. India claims their Kinetic Kill Vehicle hit Microsat-R and destroyed it in a responsible manner that limited the debris cloud lifetime to one month. The Debris Analysis Response Tool (DART) is a predictive model that can estimate the debris created from ASAT intercepts and other breakup events. The tool utilizes the target mass, projectile mass, and relative velocity to statistically model debris created from a fragmentation event. This report evaluates India's claim that the debris cloud will disperse and reenter in the weeks following the intercept.

16:30 AAS 19-674 Tracking and Maneuver Detection for Large Satellite Constellations Using a Partitioned GLMB Filter and Smoother
Benjamin Reifler, The University of Texas at Austin; Brandon Jones, University of Texas at Austin

Previously, tracking of large satellite constellations with the generalized labeled multi-Bernoulli (GLMB) filter was computationally intractable for myopic sensors, as the large number of unobserved targets at each step would lead to an exponentially increasing number of hypotheses. By partitioning the label space based on assumed independence between distant measurements, the overall tracking problem can be decomposed into smaller, tractable sub-problems. Using this technique, the GLMB filter will be used to track a simulated 4,425-satellite constellation observed by a limited number of myopic sensors and the GLMB smoother will be used to improve tracking performance and enable maneuver detection.

16:50 **AAS 19-807** **A Technique for Space Object Catalog Evaluation**

Alan Segerman, U.S. Naval Research Laboratory; Zachary Sibert, Naval Research Laboratory; Felix R. Hoots, Aerospace Corporation; Paul Schumacher, Air Force Research Laboratory

An ever-increasing number of non-U.S. governmental entities is collecting observations of orbiting objects, and constructing space object catalogs that are independent of the operational catalog maintained by Air Force Space Command. With this proliferation of cataloging, it becomes necessary to evaluate the quality of the resulting orbit catalogs. Using the operational U.S. military catalog as a baseline reference, a simple yet robust method of evaluating alternative space object catalogs has been developed, focusing on catalog completeness, accuracy, and timeliness. A full description of the evaluation methodology is presented, along with a prototypical set of results.

Aug 14, 2019 Eastland Ball Room

Trajectory Design & Optimization V

Chair: David B. Spencer, Pennsylvania State University

13:30 **AAS 19-909** **Flyby in the spatial three-body problem**

Davide Menzio, Politecnico di Milano; Camilla Colombo, Politecnico di Milano

The extension of Flyby map from the planar to the spatial circular restricted three-body problem is presented. The substitution of the longitude of the apsis with the relative angular distance allows to obtain an equi-dimensional parametrisation of the phase-space but able to set boundary conditions of the integration process with three-dimensional Poincaré sections that are mapped on each other. Different parametrisation strategies are discussed, and the improved Flyby map is used to give insight on the dynamics of low-energy flyby at different inclinations. An example trajectory of Europa Clipper mission is given for conditions all outside the linked-conics applicabity domain.

13:50 **AAS 19-912** **Risk-aware Trajectory Design with Continuous Thrust: Primer Vector Theory Approach**

Kenshiro Oguri, University of Colorado Boulder; Jay McMahon, University of Colorado Boulder

This two-part series shares the common objective: design optimal spacecraft trajectories with guaranteed safety, with different focuses in terms of the orbit control approaches. This paper presents a framework for solving risk-aware trajectory design problems with continuous thrust. In contrast to the impulsive maneuver case, we are no longer able to take convex optimization approaches for the continuous-thrust problems. Instead, this paper takes a direct/indirect hybrid numerical optimization approach with a chance-constrained version of the classical primer vector theory. The chance-constrained primer vector analytically provides the optimal control directions taking into account the safety constraints under uncertainties.

14:10 **AAS 19-749** **SPACECRAFT MANEUVER STRATEGY OPTIMIZATION FOR DETECTION AVOIDANCE USING REACHABILITY SETS**

Connor Clary, Pennsylvania State University; Jason Reiter, Penn State ARGoPS; David B. Spencer, Pennsylvania State University

The Conjugate Unscented Transform allows for an easy calculation of reachability sets with a minimal number of full model propagations. The computation time savings that come with this method encourages implementation of reachability sets in more complex problems. Spacecraft maneuver planning for detection avoidance is unique in that all objectives may not be met by moving some minimum distance from the nominal orbit. Combining ground-track manipulation and propellant-use in reachability-based multi-objective optimization gives planners a unique perspective when designing detection avoidance maneuvers. Taking into account multiple maneuvers provides an advantageous opportunity to optimize a complete maneuver strategy for detection avoidance.

14:30 AAS 19-895 Optimal Inspection Trajectories with Enforcement of Chief and Inspector-Centered Dynamic Zone Constraints

Mark Mercier, U.S. Air Force; Kirk W. Johnson, US Air Force

The need for on-orbit optimal inspection missions has risen with the aging of important legacy space assets. It is of interest to complete inspection missions without interruption of mission operations which can be simulated via dynamic keep-in and keep-out zone constraints. In addition, inspection pointing requirements must be captured via a body-fixed, inspector-centered keep-in zone constraint. This study implements a technique capable of finding the optimal inspection trajectory in the presence of multiple dynamic zone constraints which are either chief or inspector-fixed. This technique is proven in an example scenario with additional parameter sensitivity analysis.

14:50 AAS 19-701 A Time-Dependent TSP Formulation for the Design of an Active Debris Removal Mission using Simulated Annealing

Lorenzo Federici, Sapienza University of Rome; Alessandro Zavoli; Guido Colasurdo, Università di Roma Sapienza

This paper proposes a formulation of the Active Debris Removal (ADR) Mission Design problem as a modified Time-Dependent Traveling Salesman Problem (TDTSP). The TDTSP is a well-known combinatorial optimization problem, whose solution is the cheapest mono-cyclic tour connecting a number of non-stationary cities in a map. The problem is tackled with an optimization procedure based on Simulated Annealing, that efficiently exploits a natural encoding and a careful choice of mutation operators. The developed algorithm is used to simultaneously optimize the targets sequence and the rendezvous epochs of an impulsive ADR mission. Numerical results are presented for sets comprising up to 20 targets.

15:10 AAS 19-831 HelioSwarm: Swarm Mission Design in High Altitude Orbit for Heliophysics

Laura Plice, Metis Technology Solutions; Andres Dono, NASA Ames Research Center/MEI; Stephen West, Metis Technology Solutions

HelioSwarm is a mission concept that will deploy multiple, co-orbiting satellites to use the solar wind as a natural laboratory for understanding the fundamental, universal process of plasma turbulence. The HelioSwarm transfer trajectory and science orbit use a lunar gravity assist to deliver the ESPA-class nodes attached to a large data transfer hub to a P/2 lunar resonant orbit. In the science orbit, the free-flying nodes use simple Cartesian relative motion patterns to establish baseline separations both along and across the solar wind flow direction.

15:30 Afternoon Break

15:50 AAS 19-686 Constructing a Set of Motion Primitives in the Circular Restricted Three-Body Problem via Clustering

Thomas Smith, University of Colorado Boulder; Natasha Bosanac, University of Colorado, Boulder

To reduce the complexity of trajectory design in chaotic environments, data analysis techniques support the representation of a large and diverse solution space by a fundamental set of governing structures. In this paper, clustering algorithms are used to construct a set of motion primitives that summarize families of periodic orbits and their invariant manifolds in the Circular Restricted Three-Body Problem. Furthermore, the impact of various clustering algorithms and feature vector definitions on the resulting set of primitives is explored. These primitive sets are then used to construct a transfer in the Earth-Moon system, demonstrating their value for rapid trajectory design.

16:10 AAS 19-829 Trajectory Design for a Solar Polar Observing Constellation

Thomas Smith, University of Colorado Boulder; Natasha Bosanac, University of Colorado, Boulder; Thomas Berger, University of Colorado Boulder; Nicole Duncan, Ball Aerospace & Technologies Corporation; Gordon Wu, Ball Aerospace & Technologies Corporation

Space-based assets are essential in providing advanced geomagnetic storm warnings caused by solar activity. Most space weather satellites obtain measurements of the Sun's magnetic field along the Sun-Earth line and in the ecliptic plane. To obtain complete and regular polar coverage, the University of Colorado Boulder's Space Weather Technology, Research and Education Center (SWxTREC) and Ball Aerospace are currently developing a mission concept labeled the Solar Polar Observing Constellation (SPOC). The focus of this paper is the systematic trajectory design approach used to develop a baseline solution for the SPOC mission to improve solar magnetic field models and wind forecasts.

16:30 AAS 19-811 A Unified Framework for Aerocapture Systems Analysis

Athul Pradeepkumar Girija, Purdue University; Sarag Saikia, School of

Aeronautics and Astronautics, Puurdue University; James Cutts, NASA Jet Propulsion Laboratory; James Longuski, Purdue University

We propose a unified method to analyze the end-to-end aerocapture design space. The present work introduces a single chart to concisely capture the interdependencies among launch vehicle performance, interplanetary trajectory trades, and vehicle performance for an aerocapture mission concept. The proposed method enables the mission designer to perform a rapid and comprehensive analysis of the underlying trade space. We illustrate the proposed method with its application to a Neptune aerocapture mission. Results indicate Neptune aerocapture using high energy trajectories not considered in previous studies can utilize heritage blunt body aeroshells and allow a five year reduction in flight time.

16:50 AAS 19-848 OPTIMAL SPACECRAFT DOCKING MANEUVER USING DIRECT AND INDIRECT COLLOCATION METHOD AND PARTICLE SWARM OPTIMIZATION

Damien GUEHO, The Pennsylvania State University; Guanwei He, Pennsylvania State University; Puneet Singla, Pennsylvania State University; Robert Melton, Pennsylvania State University

In this paper, two different optimization methods, direct and indirect, are investigated to solve an optimal spacecrafts docking maneuver problem. Both direct and indirect collocation methods are implemented and results from these two optimization methods are compared and discussed. While these two methods focus on minimum time maneuver problem, minimum energy problem and a combination of minimum time and minimum energy problem are solved using direct collocation method. Results show that indirect collocation method with a good guess performs better than a purely direct approach.

17:10 AAS 19-815 Aerocapture Performance Analysis for a Neptune Mission Using a Heritage Blunt-Body Aeroshell

Athul Pradeepkumar Girija, Purdue University; Sarag Saikia, School of Aeronautics and Astronautics, Puurdue University; James Longuski, Purdue University; Shyam Bhaskaran, Jet Propulsion Laboratory; Matthew Smith, NASA Jet Propulsion Laboratory; James Cutts, NASA Jet Propulsion Laboratory

Previous Neptune aerocapture studies used a mid lift-to-drag (L/D) vehicle with L/D of 0.6--0.8. All planetary entry vehicles flown to date are low-L/D vehicles with L/D less than 0.4. Lack of a mid-L/D vehicle is a serious hindrance to Neptune aerocapture. Recent navigation analysis along with new guidance algorithms merit investigation of the performance of a low-L/D vehicle. Monte Carlo analysis shows that a vehicle with

L/D = 0.4 offers sufficient control authority. For 2000 simulated trajectories with worst case dispersions, only one trajectory resulted in partial failure while all the others achieved the target orbit successfully.

Aug 14, 2019 Rines A

Conference Administration Subcommittee Meeting

Aug 14, 2019 Winslow Homer

Technical Activities Subcommittee Meeting

Aug 14, 2019 Longfellow

Web Administration Subcommittee Meeting

Aug 15, 2019 Winslow Homer

Attitude Dynamics & Control II

Chair: John Christian, Rensselaer Polytechnic Institute, Kenneth Horneman, Emergent Space Technologies, Inc.

8:00 **AAS 19-812** **ATTITUDE DETERMINATION STRATEGY BASED ON KALMAN FILTER FOR THE SPORT CUBESAT SCIENCE MISSION**

Kátia Maier dos Santos, Universidade Federal de Santa Maria (UFSM); Willer Gomes dos Santos, Aeronautics Institute of Technology (ITA); Valdemir Carrara, Aeronautics Institute of Technology (ITA); Charles Swenson, Utah State University (USU); Lidia H. S. Sato, Aeronautics Institute of Technology (ITA); Luis E. V. L. Costa, Aeronautics Institute of Technology (ITA); André Luís da Silva, Universidade Federal de Santa Maria (UFSM)

The Scintillation Prediction Observations Research Task (SPORT) is a 6U CubeSat mission whose primary objective is to improve the understanding of nature and evolution of ionospheric structures around the sunset to improve predictions of disturbances affecting the propagation of radio and telecommunication signals. During the blind zones of the star sensor, the attitude determination method should be based on information provided by magnetometer, solar sensor and gyroscope, although with degraded accuracy. This paper investigates if the attitude determination process of the SPORT CubeSat could be improved, in terms of accuracy, by using estimation algorithm and an Extended Kalman Filter.

8:20 **AAS 19-665** **Efficient B-dot Law for Spacecraft Detumbling**

Mohammed Desouky, Michigan Technological University ; Ossama Abdelkhalik, Iowa State University

The detumbling B-dot law and its variants assume high angular velocity. Once the angular velocity becomes small (near the end of detumbling maneuver), this assumption causes longer detumbling time and larger power consumption. A novel variant of B-dot control law is proposed that eliminates the drawback of this assumption using a more accurate relation between the angular velocity and the magnetic field rates. Intensive Monte Carlo runs show that the proposed B-dot law consumes much less power and performs faster detumbling compared to current B-dot laws.

8:40 **AAS 19-935** **Evaluating the Stability Boundary and Derivation of a Sufficient Condition for Second Order Repetitive Control**

Ayman Ismail, Columbia University; Richard Longman, Columbia University;

Peiling Cui, Beihang University; Zhiyuan Liu, Beihang University; Han Xu, Beihang University

Repetitive Control (RC) is an effective method to eliminate jitter in spacecraft. The frequency response of first order RC has narrow notches at the addressed frequency, requiring accurate knowledge of the disturbance period. With imperfect knowledge, or with fluctuations in the period, the performance is compromised. This paper studies second order repetitive control designed to reduce sensitivity to period. The stability condition is more complicated. The paper gives an algorithm to evaluate it. A sufficient stability condition is derived, which is much easier to use. The paper evaluates how close the sufficient condition is to the true stability boundary.

9:00 **AAS 19-765** **Opportunities and Limitations of Adaptive Augmented Control for Launch Vehicle Attitude Control in Atmospheric Flight**

Domenico Trotta, Sapienza University of Rome; Alessandro Zavoli; Guido De Matteis, Full Professor; Agostino Neri, ESA ESRIN - VEGA Integrated Project Team

This paper focuses on the analysis of the Augmented Adaptive Control (AAC) approach for the attitude control of launch vehicles, in order to assess its effectiveness for different vehicle configurations. While classical control methods are typically able to meet requirements for flight, the AAC has been proposed to improve performance capabilities, add robustness and allow recovery from severely off-nominal, unanticipated conditions. Still, circumstances exist where AAC either degrades the performance of the baseline controller or drives the system to instability. The AAC system behavior in these circumstances is analyzed and discussed.

9:20 **AAS 19-629** **Orthogonal range searching in n-dimensional spaces using k-vector**

David Arnas, Centro Universitario de la Defensa - Zaragoza; Carl Leake, Texas A&M University; Daniele Mortari, Texas A&M University

This work introduces the n-dimensional k-vector, a new algorithm devised to perform orthogonal range searching in static databases with multiple dimensions. The algorithm presented is the evolution of the k-vector, a range searching method devised for the Star-Identification problem and part of the Pyramid star-identification algorithm. The n-dimensional k-vector has a worst case complexity of O(d(kn^{d-1})^{1/d}), where k is the number of elements retrieved, n is the number of elements in the database, and d is the number of dimensions of the problem. This manuscript includes a detailed description of the methodology as well as a study of the algorithm

9:40 **AAS 19-833** **Relative Positioning and Tracking of Tethered Small Spacecraft Using Optical Sensors**

Yanjie Guo, Georgia Institute of Technology ; Brian Gunter, Georgia Institute of Technology

This study analyzes the attitude dynamics and tracking control system for an object attached via tether to a primary spacecraft using optical sensors. Requirements of the tracking include body pointing of the main spacecraft to the tethered target, in addition to optimized sun pointing for maximum power generation from the primary spacecraft's solar panels. This study shows that a modified PD controller with 3 reaction wheels can track the tethered object given only relative position information, i.e. the relative target position and the sun pointing vector in the body frame, generated from an optical camera and sun sensor.

10:00 **Morning Break**

10:20 **AAS 19-884** **Proof of Stable Inverses not Involving Factorization and Evaluations of Their Superiority**

Xiaoqiang Ji, Columbia University MC4703 ; Richard Longman, Columbia University

Various kinds of control would like zero tracking error, iterative learning control, repetitive control, adaptive control. Spacecraft applications include on-board fine pointing sensors, jitter cancellation. Zero tracking error solves an inverse problem, what command produces the desired output. However, digital control systems usually have unstable inverses, preventing the design of such controllers. A previous paper at this conference, created ways to bypass this instability problem. This paper supplies a proof for stable inverses that do not factorize the relevant dynamic matrix, then examines the behavior of all these solutions. The conclusion, the new stable inverse designs are to be preferred.

10:40 **AAS 19-653** **Time-varying feedback for attitude regulation in prescribed finite-time**

Marcelino Mendes de Almeida, The University of Texas at Austin; Maruthi R. Akella, The University of Texas at Austin

This paper introduces a finite-time feedback stability controller for rigid-body attitude dynamics subject to full actuation. The control structure is Lyapunov-based and is designed to regulate the configuration from an arbitrary initial state to any prescribed final state within user-specified finite transfer-time. The synthesis of the control structure is explicit, i.e., given the transfer-time time, the feedback-gains are explicitly stated to satisfy the convergence specifications. Differently from previous works, the proposed controller satisfies the reduction self-property for attitude controllers, eliminating the need to have precise knowledge of the system's inertia tensor.

11:00 **AAS 19-664** **Efficient Magnetic Attitude Regulation Control**
Mohammed Desouky, Michigan Technological University ; Ossama Abdelkhalik, Iowa State University

The activation of magnetic rods generates magnetic field that causes time varying errors in magnetometers measurements. To lessen this effect, the rods and magnetometers are usually activated alternatively, leading to increased maneuver time, power consumption, and even adding to the under actuation problem.
In this paper, a different control scheme is proposed where, at times, the magnetic field measurements are replaced by a pseudo measurements computed based on measurements of the angular velocity. This algorithm reduces the maneuver time and magnetic rods power consumption. This algorithm is verified using Monte Carlo Simulations and real telemetry data of CASSIOPE spacecraft.

11:20 **AAS 19-877** **Relative Attitude Control of Two Spacecraft Using Electrostatic Interactions**
John Galjanic, Embry-Riddle Aeronautical University, Daytona Beach; Dongeun Seo, Embry-Riddle Aeronautical University; Morad Nazari, Embry-Riddle Aeronautical University

This is a preliminary study on controlling the relative attitude of two spacecraft using electrostatic
torque. This study uses the multi-sphere method of Schaub and Stevenson to model two identical spacecraft and control their relative attitude in a one-dimensional rotation. The
initial results show that such a controller can feasibly control the system under consideration.
Future work will consider three-dimensional rotations and the optimal distribution of spacecraft charge to create the electrostatic torque.

11:40 **AAS 19-741** **Optimum Momentum Bias for Zero-Feedback Reaction Wheel Slews**
Lara Magallanes, Naval Postgraduate School; Mark Karpenko, Naval Postgraduate School

Unscented guidance can reduce the open-loop sensitivity to parametric and other uncertainties and enable an accurate slew to a target in the absence of feedback. It is shown that the achievable open-loop sensitivity reduction depends on the magnitude and direction of the momentum bias of a reaction wheel attitude control system. In this paper, an unscented guidance problem is formulated for finding the momentum bias that minimizes the terminal pointing error for a large angle zero-feedback slew maneuver.

Aug 15, 2019 Longfellow

Space Situational Awareness & Conjunction Analysis

Chair: Matthew Wilkins, L3 Applied Defense Solutions

8:00 **AAS 19-605** **Covariance Realism is Not Enough**
J. Russell Carpenter, NASA Goddard Space Flight Center

A great deal of effort has been put into improving the practice of space situational awareness such that covariance data associated with predicted close approaches is more ``realistic."  However, ``realistic" usually has meant ``larger" and this presents a problem. In many cases, there exist multiple sources for predictive ephemerides, which may be fused to produce predictive states with smaller associated covariances. Ancillary to the fusion computation is the capability to assess consistency of the estimates. If actionable covariance information becomes available, confidence intervals on the miss distance provide a more informative alternertive to collision probability for risk assessment.

8:20 **AAS 19-858** **The YORP Effect for Tumbling Defunct GEO Satellites**
Conor Benson, University of Colorado Boulder; Daniel Scheeres, University of Colorado Boulder

Defunct GEO satellite spin states are diverse and change over time. These dynamics are largely driven by solar radiation torques through the YORP effect. Previous defunct satellite YORP studies only covered uniform rotation and the initial transition to non-principal axis tumbling. We investigate long-term tumbling evolution considering YORP and internal energy dissipation with full and averaged models. Modeling demonstrates spin-orbit coupling, uniform/tumbling cycles, resonant tumbling states, and stable tumbling. These simulation results appear to be consistent with observed evolution of the defunct GOES 8-12 satellites. Improved attitude prediction for defunct satellites will benefit SSA, active debris removal, and satellite servicing.

8:40 **AAS 19-846** **Very Low Resolution Spacecraft Recognition and Pose Estimation for Close-Range Rendezvous and Proximity Operations**
William Bezouska, University of Southern California; Ryan Williams, The Aerospace Corporation; Daniel Hernandez, The Aerospace Corporation

We present machine learning approaches for the identificaiton and pose estimation of nearby spacecraft during proximity and rendezvous operations using very low resolution images. These images may include challenging illumination conditions such as shadowing or specular reflection. Spacecraft identificaiton from a known set of spacecraft is conducted using convolutional nueral networks trained on rendered low resolution images of the spacecraft. Pose estimation is conducted using a regression-based approach trained on a rendered set of high resolution images. Results indicate that identificaiton and pose estimation can be successful for object as small as 20 pixels.

9:00 **AAS 19-905** **CubeSats Hovering Collision Probability**

Ken Chan, Chan Aerospace Consulting; Yuchen Xie, Beijing Institute of Technology; Jingrui Zhang

Analytical expressions are obtained for computing the collision probability of an orbiting CubeSat hovering in the close vicinity of another CubeSat, both having time-dependent probability density functions. Studies of collision probability as a function of time are performed in terms of the parameters: separation between neighboring orbiters, covariance size (different in three directions) and the covariance growth rates. It was found that certain combinations of parameters resulted collision probability time curves which intersected and others did not. This curve-crossing phenomenon cannot be predicted in advance but must be demonstrated quantitatively by performing detailed computations.

9:20 **AAS 19-603** **Data-Driven Framework for Space Weather Modeling with Uncertainty Treatment towards Space Situational Awareness and Space Traffic Management**

Piyush Mehta, West Virginia University; Christina Kay, NASA GSFC/Catholic University of America; Richard Licata, West Virginia University; Nicholas Sia, West Virginia University

Space Weather (SW) has a strong influence on satellite tracking, orbital decay, and collision avoidance in low Earth orbit (LEO). E.g., Satellite position Probability Density Functions (*PDFs*) essential for probability of collision, *Pc*, estimates are heavily dependent on drag. The uncertainty is caused mainly due to the state of the thermosphere which is a highly dynamic environment, strongly and readily influenced by SW. Therefore, accurate SW forecasts and associated uncertainty quantification are crucial for space situational awareness and space traffic management. This paper presents a new framework for the coupling of different SW dynamical systems that also accounts for uncertainty.

9:40 **AAS 19-720** **A New Look at Predictive Probability of Collision, Predictive Maneuver Trade Spaces**

Mark Vincent, Raytheon; Theodore H. (Ted) Sweetser, Jet Propulsion Laboratory

A new analytical approach clarifies the calculations used in a formerly presented tool used to calculate the likelihood of a future probability of collision between two space objects given the current statistical information and a model of the covariance that results from future observations of the secondary object. The clarification resulted from the realization that the tool can also be used to calculate the likelihood that a collision will be missed for a chosen threshold for doing a risk mitigation maneuver. Progress on a new tool that uses the same formulation to create predictive maneuver trade space plots is reported.

10:00 Morning Break

10:20 AAS 19-869 No Feedback Multi-Sensor Tasking

Carolin Frueh, Purdue University; Bryan Little, Purdue University

Observations of resident space objects generated by sensors are the primary method of maintaining knowledge of the object states. This requires the coordination of multiple sensors with different capabilities in an optimized manner. Information exchange and processing induces time delay in a multi-sensor system that is longer than the time available to plan and start the sensor tasking step. This paper addresses this problem, an illustration is shown using TLE data in the geosynchronous region and two optical sensors with vastly different capabilities.

10:40 AAS 19-879 Design & Development Of An Optimized Sensor Scheduling & Tasking Program For Tracking Space Objects

David Shteinman, Industrial Sciences Group ; Mark Yeo, Industrial Sciences Group ; Alex Ryan, Industrial Sciences Group ; James Bennett, EOS ; Michael Lachut, EOS

The development and implementation of mathematical models and software to perform sensor scheduling and tasking for a network of sensors over a 12-hour schedule is described. The program optimizes sensor utilization by producing sensor-object assignments that maximize the information gain for each assignment window throughout the schedule..

The program accounts for asynchronous assignment windows, computing the cumulative information gain from multiple observations, scaling the information gain for high priority targets, and adding constraints on laser measurements. The program and algorithms were successfully tested on a catalogue of 20,000 objects with 6 sensors and is used to produce daily sensor schedules.

11:00 **AAS 19-600** **Space-Based Target Search Methods using an Optical Sensor Model for Space Situational Awareness**

Ryne Beeson, University of Illinois at Urbana-Champaign; Kento Tomita, University of Illinois at Urbana-Champaign ; Onalli Gunasekara; Andrew J. Sinclair, Air Force Research Laboratory; Koki Ho, University of Illinois, Urbana-Champaign

This paper develops a space-based, target search-to-tracking framework that incorporates an optical sensor model. The framework is used for analysis of dynamic steering of a space-based optical sensor to search, detect, and track unknown space objects that have highly uncertain states. The analysis with the target search framework compares information-theoretic and maximum probability target search methods to efficiently characterize a target with large uncertainty. The optical sensor modeling includes simulating a full camera frame that provides measurements for the estimation process. The target search framework is evaluated with Monte Carlo Simulations using estimated real-world case parameters. The results of the simulations demonstrate an optimized and efficient performance of the initial target search and estimation performance for SSA.

Aug 15, 2019 Hawthorne

Special Session: Artificial Intelligence in Astrodynamics II - Reinforcement Learning

Chair: Roberto Furfaro, The University of Arizona

8:00 AAS **19-640** **Value Iteration and Q-Learning for Optimal Control by High Dimensional Model Representation (HDMR)**
Minh Phan, Dartmouth College

This paper formulates High Dimensional Model Representation (HDMR) for Value Iteration, a reinforcement learning method for optimal control. HDMR models a nonlinear function as a sum of dimensionally increasing functions. A type of HDMR called cut-HDMR is used where the values of a function along multi-dimensional cuts are used to build the HDMR directly. The representation is non-parametric, thus unlike other modeling methods such as artificial neural networks or basis functions, there are no parameters to learn. The cut-HDMR is used to model both the value function and the optimal controller.

8:20 AAS **19-628** **A New approach to Autonomous Asteroid Close Proximity Maneuvers Enabled by Reinforcement Learning**
Brian Gaudet, Deep AnalytX, LLC; RICHARD LINARES, Massachusetts Institute of Technology; Roberto Furfaro, The University of Arizona

We suggest a new approach to autonomous asteroid close proximity maneuvers that does not require characterization of the dynamics or creation of a shape model. The approach uses either active beacons dropped by the spacecraft or laser illumination of the target site by an orbiter. The adaptive integrated guidance navigation, and control system is implemented as a policy optimized using reinforcement meta-learning. This policy maps observations consisting of camera images and LIDAR altimeter readings directly to engine thrust commands. We validate the system in a six degrees-of-freedom simulator, where the system must adapt to unknown environment.

8:40 AAS **19-692** **ELM-based Actor-Critic approach to Lyapunov vector fields relative motion guidance in Near-Rectilinear Orbits**
Andrea Scorsoglio, University of Arizona; Roberto Furfaro, The University of Arizona

9:00 AAS **19-703** **PREDICTING SATELLITE CLOSE APPROACHES USING STATISTICAL PARAMETERS IN THE CONTEXT OF ARTIFICIAL INTELLIGENCE.**

Alinda Mashiku, NASA GSFC; Carolin Frueh, Purdue University; Nargess Memarsadeghi, NASA; Mitchell Zielinski, Purdue University; Evana Gizzi; Alexander Burton, Purdue University

In this paper, we are introducing a new approach based on the latest capabilities in machine learning (neural networks) to allow the potential for fast and accurate close approach predictions. We consider the study of statistical and information theory parameters instead of the classical probability of collision computation, in order to determine the feasibility of reliably predicting and giving confidence intervals for collisions. The goal is to assess whether the resulting outputs can be understood, applied, and implemented as a close approach decision-making tool.

9:20 AAS 19-822 Contingency Planning in Complex Dynamical Environments via Heuristically Accelerated Reinforcement Learning

Ashwati Das-Stuart, Purdue University; Kathleen C. Howell, Purdue University

Unexpected events can cause a spacecraft to significantly deviate from its nominal transfer path, leading to undesirable impacts on the mission. In such scenarios, the capability for rapid trajectory re-design is key for mission success. This investigation leverages a reinforcement learning strategy to automate the search for a route to restore the overall mission goals after a spacecraft experiences a deviance in its thrusting capabilities during nominal operations. The route is computed by exploiting natural dynamical flows and accommodating spacecraft propulsive capabilities to construct an initial guess that is then transitioned to a continuous solution via traditional optimization techniques.

9:40 AAS 19-680 Reinforcement Learning and Topology of Orbit Manifolds for Stationkeeping of Unstable Symmetric Periodic Orbits

Davide Guzzetti, Auburn University

This work investigates reinforcement learning (RL) as an algorithm for orbit stationkeeping within chaotic environments. We first consider maintenance of unstable symmetric periodic (USP) orbits within circular restricted three-body problem (CR3BP) dynamics. Because topology for USP orbit dynamics is largely understood, USP orbits may be a testing ground to explore maintenance strategies based on RL models. Existing stationkeeping algorithms, including Floquet mode and gradient-based optimal control, may also supply a reference for characterizing RL performance. Outlining fundamental RL mechanisms for orbit stationkeeping and describing their relation to existing orbit maintenance techniques will support similar applications within more complex scenarios.

10:00 Morning Break

10:20 AAS 19-751 SPACECRAFT MANEUVER STRATEGY OPTIMIZATION FOR DETECTION AVOIDANCE USING REINFORCEMENT LEARNING

Jason Reiter, Penn State ARGoPS; David B. Spencer, Pennsylvania State University

Spacecraft maneuvers are planned with operational objectives in mind, usually ranging from making up for orbit perturbations to maneuvering to avoid a possible collision. Though these areas have been researched in depth, performing maneuvers to avoid detection by sensors hasn't been explored until recently. Reinforcement learning has been shown to be an effective method for optimizing a single detection avoidance maneuver for the purpose of avoiding detection. This work expands on that further by optimizing the maneuver strategy itself that will result in a spacecraft continually avoiding detection through-out a desired time period given a nominal tasking strategy for the

10:40 AAS 19-907 Evaluation of Use of Zero Phase Circulant Low Pass Filters for Robustification of Iterative Learning Control

Tianyi Zhang, Columbia University; Richard Longman, Columbia University

Iterative Learning Control (ILC) repeatedly executes a trajectory, repeatedly adjusting the command, aiming to converge to zero tracking error. Spacecraft applications include fine pointing sensors doing repeated scanning maneuvers. Zero error implies zero for all frequencies to Nyquist. Usually, high frequency residual modes / parasitic poles cause learning instability. Zero-phase low-pass filtering was introduced to produce stability robustness. Previous work showed that handling of initial conditions in such filters can cause instability. Circulant filtering was suggested to circumvent such a possibility. This paper investigates in detail how circulant filters can be applied, and compares to other filtering methods.

Aug 15, 2019 Eastland Ball Room

Trajectory Design & Optimization VI

Chair: Rohan Sood, University of Alabama

8:00 **AAS 19-929** **Unconstrained Spacecraft Trajectory Optimization using Embedded Boundary Value Problems**

David Ottesen, The University of Texas at Austin; Ryan Russell, The University of Texas at Austin

An optimization algorithm is described that leverages many solutions to embedded boundary value problems along a spacecraft trajectory discretized into segments. The problem formulation is purely unconstrained leading to fast runtimes on the order of minutes for hundreds of segments producing up to 50 revolutions. Within the algorithm, exact first-order gradients and the Broyden-Fletcher-Goldfarb-Shanno correction for the search direction contains a matrix manipulation that is equal in runtime to the cost and partials at 350 nodes and eventually limits the problem size to 1200 nodes. The algorithm minimizes fuel or energy, models time-free transfers, and approximates high and low thrust.

8:20 **AAS 19-806** **L2 Station Keeping Maneuver Strategy for the James Webb Space Telescope**

Jeremy Petersen, a.i. solutions; Karen Richon, NASA GSFC

The station-keeping strategy for the James Webb Space Telescope (JWST) implements a differential corrector to determine the delta-v to achieve zero velocity in the x-component of the rotating libration point frame at the fourth crossing of the Earth-Sun line. Research and application demonstrate that maneuvering along the stable eigenvector of the monodromy matrix produces a minimum solution. This investigation will demonstrate the techniques developed to find the minimum maneuver direction in a full ephemeris model along with strategies used to cope with the attitude constraints imposed by the sunshield that prevents the ability to maneuver along the stable eigenvector.

8:40 **AAS 19-774** **Solar Sail Trajectories and Orbit Phasing of Modular Spacecraft for Segmented Telescope Assembly about Sun-Earth L2**

Gabriel Soto, Cornell University; Erik Gustafson, Cornell University; Dmitry Savransky, Cornell University; Jacob Shapiro, Cornell University; Dean Keithly, Cornell University

In-space assembly of a segmented primary mirror is needed to produce a large primary mirror bigger than LUVOIR, about 30m in diameter. We propose a novel mission concept for a segmented space telescope where each identical mirror segment is placed on modular spacecraft. Individual modules are launched as payloads of opportunity that self-assemble about the Sun-Earth L2 point. They use a solar sail as a means of continuous thrust propulsion. After docking, the solar sails are steered to overlap and create a planar sun shield for the telescope. We provide the framework for minimizing the total mission assembly time.

9:00 **AAS 19-926** **Maneuver planning for NISAR mission**
Francois Rogez, JPL; Sara Hatch; Allen Halsell, JPL/Caltech

NISAR, a joint NASA-ISRO science mission will require maintaining an Earth-fixed ground track and altitude to accurately repeat every 12 days.We constructed a ballistic reference trajectory that meets the science requirements but excludes some forces. The latter are treated as perturbations to be either corrected or absorbed within the requirement tolerance. Perturbation prediction errors require frequent and rapid design activities, which drive us toward automation, robust implementation, and streamlined processes. Combining a simplified model of the effect of future maneuvers, with an accurate propagation of the current trajectory provides a robust control system with appropriate accuracy given the input uncertainty.

9:20 **AAS 19-758** **Mission Feasibility from Trajectory Optimization and the State of Space Systems Research at the University of Auckland**
Darcey Graham, University of Auckland; Nicholas Rattenbury, University of Auckland; John Cater, University of Auckland

New Zealand has recently become a space-faring nation, and so is at an exciting time, forming collaborations and deciding where its interests lie. The current state of space systems research at the University of Auckland, which focuses on inexpensive small satellites, is presented with an assessment of future missions based on trajectory optimization. The low-thrust capabilities of both old and novel electric propulsion systems place significant limitations on future missions, so limiting Δv will be the objective of trajectory optimization. Different methods of trajectory optimization will be compared for the various technologies available, and the feasibility of mission plans assessed.

9:40 **AAS 19-847** **Micro-Pulsed Plasma Thruster Maneuver Characterization**
Jennifer Hudson, Western Michigan University

The Optical Plasma Spectroscopy CubeSat (OPS-Cube) will consist of a 6U CubeSat equipped with a micro-pulsed plasma thruster and an optical emission spectrometer. The mission will demonstrate on-orbit electric propulsion thruster diagnostics via optical measurements of the thruster's plasma plume. The OPS-Cube mission offers a unique opportunity to characterize the micro-pulsed plasma thruster's capabilities for small satellite orbit maneuvers. This paper will describe the orbit maneuver design for the OPS-Cube mission, including the effects of mission- and system-level constraints, the sensitivity to thrust vector misalignment, the maneuver detection strategy, and the range of feasible initial orbits for the mission.

10:00 Morning Break

10:20 AAS 19-867 Heliocentric Escape and Lunar Impact From Near Rectilinear Halo Orbits
Diane Davis, a.i. solutions, Inc.; Kenza Boudad, Purdue University; Kathleen C. Howell, Purdue University

Spacecraft departing from the Gateway in Near Rectilinear Halo Orbit (NRHO) experience gravitational forces from the Moon, Earth, and Sun, all of which can be simultaneously significant. These complex dynamics influence the post-separation risk of recontact with the Gateway and the eventual destinations of the departing spacecraft. The current investigation examines the flow of objects leaving NRHOs in the Bi-Circular Restricted Four-Body Problem, and results are applied to heliocentric escape and lunar impact trajectories in a higher-fidelity ephemeris model. Separation maneuver magnitude, direction, and location are correlated with risk of recontact with the Gateway and successful departure to various destinations.

10:40 AAS 19-893 Risk-aware Trajectory Design with Impulsive Maneuvers: Convex Optimization Approach
Kenshiro Oguri, University of Colorado Boulder; Jay McMahon, University of Colorado Boulder

Guaranteeing safety is a major concern in any space mission design. Considering asteroid orbiter missions, for example, mission designers need to plan maneuvers while avoiding hazardous risks such as impact on the asteroid surface under uncertainties. To design optimal trajectories with guaranteed safety, we propose a risk-aware trajectory design approach based on chance-constrained optimal control. As opposed to traditional state constraints, the chance-constrained approach allows us to formally deal with unbounded distributions of uncertainties such as Gaussian distributions. This paper focuses on controlling orbits with impulsive maneuvers and presents a convex optimization approach to solving the risk-aware trajectory design problems.