SPACEFLIGHT MECHANICS 2021

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Front Cover Image:

Shown is the berthing of the NG-15 Cygnus (S. S. *Katherine Johnson*) to the International Space Station (ISS) Unity node. Hooks from Unity's nadir-mounted Common Berthing Mechanism (CBM), are used to secure the spacecraft to the ISS. Launched on 20 February 2021, Cygnus NG-15 was the fifteenth launch of the Northrop Grumman robotic resupply spacecraft Cygnus, and the fourteenth flight to the ISS. Cygnus is an uncrewed vessel used to transport equipment, payloads and supplies to the ISS. Credit: NASA.

American Astronautical Society

SPACEFLIGHT MECHANICS 2021

Volume 176

ADVANCES IN THE ASTRONAUTICAL SCIENCES

Edited by
Carolin Frueh
Renato Zanetti
Jeffrey R. Stuart
Angela L. Bowes

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FOREWORD

This volume is the next in a sequence of AAS/AIAA Space Flight Mechanics Meeting volumes which are published as a part of *Advances in the Astronautical Sciences*. Several other sequences or subseries have been established in this series. Among them are: Astrodynamics (published for the AAS annually), Guidance and Control (annual), International Space Conferences of Pacific-basin Societies (ISCOPS, formerly PISSTA), and AAS Annual Conference proceedings. Proceedings volumes for earlier conferences are still available either in hard copy, digital, or in microfiche form.

Spaceflight Mechanics 2021, Volume 176, Advances in the Astronautical Sciences, consists of three parts totaling about 3,400 pages, plus a CD ROM/digital format version which also contains all the available papers.

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

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

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

AAS/AIAA SPACEFLIGHT MECHANICS VOLUMES

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

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Robert H. Jacobs, Series Editor

PREFACE

The 31st Spaceflight Mechanics Meeting, originally scheduled in Charlotte, North Carolina, was held as a fully virtual event on February 1-4, 2021. The meeting was sponsored by the American Astronautical Society (AAS) Space Flight Mechanics Committee and co-sponsored by the American Institute of Aeronautics and Astronautics (AIAA) Astrodynamics Technical Committee. Approximately 299 people registered for the meeting; attendees included engineers, scientists, and mathematicians representing government agencies, the military services, industry, and academia from the United States and abroad.

There were 206 technical papers presented in 30 sessions on topics related to space-flight mechanics and astrodynamics. Dr. Juan Carlos Dolado Perez, head of the space debris modeling and risk assessment office at CNES, France, delivered the plenary lecture titled: "Key Considerations to Guarantee Safety of Operations in Space."

The editors extend their gratitude to the Session Chairs and co-Chairs who made this meeting successful: Ossama Abdelkhalik, Nicola Baresi, Natasha Bosanac, Kenza Boudad, Arnaud Boutonnet, Pardhasai Chadalavada, Daegyun Choi, Fabio Curti, Diane Davis, Kyle DeMars, Atri Dutta, Justin Fletcher, Gunner Fritsch, Roberto Furfaro, Pradipto Ghosh, Brian Gunter, Amanda Haapala Chalk, Guanwei He, Sonia Hernandez, Marcus Holzinger, Kathleen C. Howell, Brandon Jones, Donghoon Kim, Dr. Peter Lai, Richard Linares, Manoranjan Majji, Alinda Mashiku, Piyush Mehta, Robert Melton, Jay McMahon, Christopher D. Petersen, Anil Rao, Christopher Roscoe, Ari Rubinsztejn, Andrew J. Sinclair, Rohan Sood, James Thorne, Francesco Topputo, and Powtawche Valerino.

Dr. Carolin Frueh
Purdue University
AAS Technical Chair

Dr. Jeffrey R. Stuart
NASA Jet Propulsion Laboratory
AAS General Chair

Dr. Renato Zanetti
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Part III

INTERPLANETARY TRAJECTORIES

Session Chair:

Session 1: Kathleen C. Howell, Purdue University

AAS 21-230

EVALUATION OF ITERATIVE ANALYTICAL TECHNIQUES FOR THE TRAJECTORY DESIGN OF DIRECT ORBITER MISSIONS

S. P. Parvathi* and R. V. Ramanan†

This paper deals with the evaluation of iterative analytical techniques based on patched conic and pseudostate concepts for the transfer trajectory design of direct orbiter missions. For a case study, some direct orbiter missions to Mars and Jupiter for the minimum energy opportunities are considered. The departure and arrival hyperbolic orbit parameters are generated using the iterative patched conic and iterative pseudostate techniques. The departure hyperbolic trajectory thus generated is numerically propagated under the design force model and the deviations in the achieved target/arrival hyperbolic orbits, viz. closest approach altitude, arrival hyperbolic inclination and the time of periapsis passage, are computed The computational time required for the numerical refinement of the analytical trajectory designs under a realistic force model are generated. Further, the trajectory correction maneuver required for the analytical trajectory designs to precisely achieve the desired target parameters are generated. From these studies, it is concluded that the iterative pseudostate technique gives more accurate initial guess or trajectory design for missions with long flight duration as compared to the iterative patched conic technique. Particularly for missions to Jupiter or the Type II missions, the pseudostate technique fares well. However, for type I missions which has lesser flight duration, the iterative patched conic technique provides a better initial guess for the trajectory design.

[View Full Paper]

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AAS 21-261

TRANSFER BETWEEN PLANAR AND 3D QUASI SATELLITE ORBITS AROUND MARS'S MOON PHOBOS: APPLICATION TO JAXA'S MMX MISSION

Stefanos Charkoutsis,[*] Elisabet Canalias,[†] and Stefania Soldini[‡]

This research paper is focused on the optimization of a two-impulse transfer trajectories between a planar orbit and a special orbit around Phobos, as part of JAXA's Martian Moon eXploration (MMX) mission. MMX will send a spacecraft to explore the origin of the two moons of Mars: Phobos and Deimos. MMX is in collaboration with the French (CNES) and German (DLR) space agencies and this article focuses on the activities led by CNES. Initially, the theoretical minimum and maximum maneuver costs were computed for the transfer between Quasi Satellite Orbits (QSOs) and compared with data from CNES1. Then, the investigation and computation of medium altitude planar QSOs (50 x 100 km) and 3D QSOs (50 x 100 x Az) was carried out and compared with CNES' one-impulse maneuver strategy. From this comparison, it has been observed that although minimization of the two-impulse costs has been achieved the single-impulse maneuver approach seems to reach better performance.

[View Full Paper]

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AAS 21-295

DEEP SPACE TRANSFERS OF PIGGY-BACK MICRO SPACE PROBES USING HYBRID ROCKET KICK MOTOR

Daichi Ito,* Nishanth Pushparaj,† Kotaro Fujiwara,‡ and Yasuhiro Kawakatsu§

Geostationary Transfer Orbit (GTO) is a good launching point for deep space missions. Although "piggy-back" is a low-cost approach to insert a micro space probe into a GTO, the primary mission primarily determines GTOs' nature and the launch dates for piggy-back satellites. Therefore, the piggy-back probes' hybrid kick motor must have the necessary capacity to cope with arbitrary launch dates and GTOs. Preliminary studies suggest that ΔV required for the transfer from GTO to the Moon is possible with a single ignition of 1.81 km/s. This study extends the transfer case to Mars, directly and by utilizing an Earth swing-by. ΔV required for the transfers from GTO to Mars via direct orbit insertion and through Earth synchronous orbit (ESO) are studied. Results suggest that an ESO enabled transfers to Mars to reduce the transfer ΔV of 4.51 km/s to 3.69 km/s. These results provide useful insights for designing the propulsion system and planning deep space piggy-back missions.

[View Full Paper]

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AAS 21-300

APPLICATION OF HALO ORBIT ON EXTENSION FOR LAUNCH WINDOW LIMITED BY DIRECT EARTH-MARS TRANSFER

Zhe Xu,* Mai Bando,† Hideaki Ogawa,‡ and Shinji Hokamoto§

This paper proposes a method to optimize Earth-Mars transfer trajectory exploiting stable and unstable manifolds of halo orbit in the Sun-Earth system to address the limitations associated with risk and limited launch windows, which are common with traditional direct Earth-Mars transfer approaches. To mitigate the large-scale computational cost associated with this multidimensional problem, a surrogate-assisted design methodology is employed in conjunction with highly parallelized computation using GPU. The structure of the solutions is investigated in terms of the ability of halo orbits to serve as a phasing orbit for interplanetary. Results demonstrate the feasibility of the transfer strategy as well as the potential of the proposed method to serve as an efficient and constructive approach in practical mission design.

[View Full Paper]

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AAS 21-330

EARTH-TO-MARS LOW ENERGY TRANSFERS FROM CISLUNAR DIRECT RETROGRADE ORBITS

Colas Chevailler,* Emmanuel Blazquez,† and Stéphanie Lizy-Destrez‡

The scope of this research is to propose new impulsive transfer strategies from Earth-Moon DROs to Sun-Mars planar Lyapunov Orbits, making use of lowenergy pathways and weak stability boundaries. The trajectory is optimized in three patched Three-Body systems to make use of an intermediary phasing planar Lyapunov Orbit of the Sun-Earth system. The main contributions of this work are twofold. Firstly, a new strategy for cost-efficient departure from DROs is showcased, by injection into the unstable invariant manifold of a tangential planar Lyapunov Orbit. It is a continuation of previous works conducted by the authors. Secondly, a systematic hybrid optimization procedure is proposed to design fuel and time efficient DRO-to-Mars trajectories easily corrected in high-fidelity models. The trajectory design puts an emphasis on smooth correction in the Ephemeris, in order to have as marginal difference as possible between the budgets at the output of the optimization and the ones of the Ephemeris-corrected trajectory.

[View Full Paper]

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AAS 21-370

SOLAR SAIL TRAJECTORIES FOR INTERSTELLAR OBJECT RENDEZVOUS

Daniel Miller,[*] Damon Landau,[†] Richard Linares,[‡] Benjamin Weiss,[§] and Paulo Lozano[**]

The solar sail “statite” concept presents a potential means to study Interstellar Objects (ISOs). These objects are tantalizing scientific targets but challenging to study due to their short lead time and high heliocentric velocities. By using its solar sail to “hover” in place, a statite is able to await the discovery of an ISO and, when called upon, convert the enormous potential energy of its stationary state into the velocity necessary to rendezvous with the object. This investigation includes both launch trajectories to strategic statite states from Earth, and optimal solar sail trajectories to the two known ISOs: ’Oumuamua and Borisov.

[View Full Paper]

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DEBRIS CLOUDS, DEBRIS DENSITIES, AND SPACE ENVIRONMENT

Session Chair:

Session 2: Alinda Mashiku, NASA GSFC

AAS 21-200

DEBRIS RISK TRUTH DATA GENERATION FOR MODEL VALIDATION*

Brian W Hansen†

Assessing satellite risk from breakup debris has become increasingly important. Several different risk models have been developed, but there are still no truth data available for their evaluation. We present a limited set of debris risk "truth" data generated by performing massive Monte Carlo runs, preserving close approaches small enough to collide with actual satellites. Resulting risk values with error bars are presented for the FY-1C ASAT, run against three high-risk satellites. Comparisons with the corresponding risk predicted by models developed at The Aerospace Corporation show them to be conservative and accurate to within about half an order of magnitude.

[View Full Paper]

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* Approved for public release. OTR 2021-00281.

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AAS 21-217

EFFECT OF PERTURBATIONS ON ORBITAL DENSITY USING EULERIAN ORBIT DYNAMICS

Liam M. Healy[*]
Blake Halpin[†]
Scott Kindl[‡]

The behavior of object density after a fragmentation has been analyzed using “Eulerian orbit dynamics”, our term for the propagation of densities, rather than points. We previously pioneered a technique that propagates the spatial density of orbital objects exactly. In the present work, we show the effects of the J_2 gravitational perturbation on the density evolution from a low-earth orbit fragmentation. The fractional change in density due to the perturbation averages on the order of a tenth of a percent.

[View Full Paper]

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AAS 21-268

SOME TOPOLOGICAL PROPERTIES OF KEPLERIAN PARAMETRIC SCATTER DIAGRAMS OF DEBRIS CLOUDS

Ken Chan*

This paper discusses some topological properties exhibited by scatter diagrams such as semi-major axis/eccentricity, semi-major-axis/inclination and eccentricity/inclination of the debris fragments produced either in a collision between two orbiting objects or the explosion of an orbiting object. It is assumed that the velocity perturbations imparted to the debris fragments are almost spherically isotropic but do not necessarily obey a Gaussian distribution. Using this generally accepted model, it is possible to obtain characteristics of the Keplerian scatter diagrams that are not exhibited in their Cartesian analogs. These properties are useful in the study of debris clouds including their evolution and decay of various fragments due to atmospheric drag. The approach circumvents the need to perform time-consuming numerical simulations which mask certain features so important in the prediction of the life span of these debris clouds.

[View Full Paper]

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DENSITY WAVES IN DEBRIS CLOUDS

Ken Chan*

This paper shows the existence of waves of varying densities travelling through a debris cloud as it evolves after a collision between two objects orbiting in the Earth's gravitational field. It deals with the formulation of analytical expressions describing the formation and evolution of these density waves. It is well-known that the Earth's oblateness causes a precession of the Ascending Node of the orbital plane of each debris fragment. However, in contrast, these density waves are caused by ***different*** rates between the fastest and the slowest precessions belonging to the same debris cloud so as to form a band initially. As the width of this band expands, it gradually fills the Earth's 360° girth.

After that, overlapping of Ascending Nodes begins thus resulting in increased narrower bands of comparatively higher density of debris fragments in the same debris cloud. Consequently, a density wave is created whose shape is dependent on the precession rate and orbital position of each fragment. Likewise, this phenomenon simultaneously occurs with the debris fragments belonging to the other debris cloud whose bandwidth expands at a different rate. When both debris clouds have completed the longitudinal coverage, they initiate a cross effect contributing to the shape and variation of density waves. Quantitative results are obtained based on data derived from the Iridium 33/ Cosmos 2251 collision which occurred about 12 years ago. Analysis indicates that the bandwidth of the Cosmos debris cloud expands about 4.5 times the rate as the Iridium cloud and has just completed 9 full 360° girths.

In the coming years, more and more density waves (with diminishing amplitudes) of the Ascending Node will be formed in each debris cloud. Moreover, the narrowing of neighboring orbits causes the density to increase with latitude. The asymptotic steady state for the Cosmos debris cloud is that the density of debris fragments is uniform along the equator and proportional to the secant of the argument of latitude. The Iridium debris cloud will not reach this state.

[View Full Paper]

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AAS 21-286

SECULAR DYNAMICS BASED FEATURES FOR THE CHARACTERIZATION OF SMALL DEBRIS CLOUDS AFTER FRAGMENTATION

Di Wu* and Aaron J. Rosengren†

Characterizing space debris fragmentation event, the most frequently happening debris generating event, is vital for a better understanding over the past, current, and future space environment. Limited space surveillance resources inevitably results in a lagged coverage of such event, thus requiring further detailed analysis over individual case. In addition, the chaotic feature of fragmentation would render a complex dynamics condition for the generated space debris cloud. In this research, we proposed a method to specify a reduced number of space debris from the whole space debris cloud generated by chaotic fragmenting; selected space debris are used to trace back breakup event. This method could avoid the chaotic performance induced by fragmenting while dramatically reduce calculations in backward propagation.

[View Full Paper]

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AAS 21-340

DENSITY ESTIMATION USING SECOND-ORDER GAUSS-MARKOV PROCESSES

Vishal Ray,* Daniel J. Scheeres,† Eric K. Sutton,‡ and Marcin Pilinski§

In the orbit determination and prediction of low Earth orbit (LEO) satellites, atmospheric drag introduces the largest uncertainties. This is mainly because of errors in atmospheric models that are used to provide densities along the orbit to the estimator. But averaging out time-variations in the drag-coefficient by estimating it as a constant also serves as a significant error source. Additionally, drag-coefficient errors also feed into estimates of orbit-derived atmospheric densities. The best solution to the problem would be the ability to simultaneously estimate both the density and drag-coefficient from tracking data but the difficulty lies in the lack of observability of the two parameters. We leverage previous work on using Gauss-Markov processes to model density corrections and Fourier drag-coefficient models to propose a method to simultaneously estimate both the drag-coefficient and density during orbit determination.

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AAS 21-354

ASSESSING THERMOSPHERIC DENSITIES DERIVED FROM ORBITAL DRAG DATA

Valerie Bernstein,[*] Marcin Pilinski,[†] and Eric Sutton[‡]

Thousands of satellites and debris reside in the thermosphere. The United States Space Command archives orbital tracking data for most known Earth-orbiting artificial satellites in the form of Two-Line Element (TLE) entries, which provide an expansive record of historical orbital element information. TLEs have been used to assess variability and trends in thermospheric temperature and density. Density can be extracted from TLEs through processing methods which propagate the orbital trajectory and assess orbital mean motion changes with time for a satellite. Comparisons between TLE-derived densities and high-accuracy accelerometer-derived densities for 8+ years of CHAMP and GRACE satellite data indicate that TLE processing choices, particularly those involving the time window of integration, significantly impact the agreement between the different density datasets. Integration time windows of ≥8 days improve the relative accuracy of TLE-derived densities, though analysis reveals a persistent bias associated with trailing GRACE satellite comparisons. An error model for TLE-derived densities is presented, which can provide lower bound uncertainty estimates for TLEs. This error analysis is useful for understanding the uncertainties in long-term density datasets and trends inferred from TLEs used to construct empirical models.

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AAS 21-415

IMPACT OF DRIVER AND MODEL UNCERTAINTY ON DRAG AND ORBIT PREDICTION

Richard J. Licata,[*] Piyush M. Mehta,[†] and W. Kent Tobiska[‡]

The capability to accurately model and subsequently forecast thermospheric density is imperative for satellite orbit prediction and conjunction operations. Two of the major sources of uncertainty are Space Weather (SW) driver uncertainty and the underlying uncertainty within the density models, called model uncertainty. These uncertainties propagate into drag estimates and therefore satellite position estimates, which require confidence in decision making with regards to avoidance maneuvers. In this paper, we quantify the impact of SW driver forecast uncertainty and, for the first time, model uncertainty on drag and orbit prediction.

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RENDEZVOUS

Session Chair:

Session 3: Fabio Curti, School of Aerospace Engineering, Sapienza University of Rome

AAS 21-209

BEARINGS-ONLY GUIDANCE FOR RENDEZVOUS IN A CIS-LUNAR NRHO

Fabio D'Onofrio,* Giordana Bucchioni,† and Mario Innocenti‡

The current plans of returning to the Moon involve rendezvous and docking/berthing with the Lunar Gateway, whose targeted orbit is a Near Rectilinear Halo Orbit. In this work, a guidance algorithm for the close-range rendezvous phase of the proposed lunar sample return mission HERACLES is designed, assuming the chaser can measure relative angles only to the target. The navigation performance is affected by the maneuvers performed because their execution is necessary to make the problem observable. The relative motion equations with third body perturbation are considered directly in the guidance algorithm, with the additional aim of improving observability during the approach trajectory.

[View Full Paper]

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AAS 21-235

ANALYTICAL DESCRIPTION OF RELATIVE POSITION AND VELOCITY ON J2-PERTURBED ECCENTRIC ORBITS

Matthew Willis[*] and Simone D'Amico[†]

A new solution is introduced for the relative position and velocity of two spacecraft on eccentric orbits perturbed by Earth oblateness. The equations of relative motion subject to an arbitrary perturbing force are derived and this general framework is used to develop a partial solution for the case of perturbation by the second zonal harmonic of Earth's gravitational potential. The performance of the new solution is compared with several prominent solutions from the literature, and the inability of variation of parameters to produce a complete, closed-form solution for the J_2 corrections is discussed.

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AAS 21-281

NON-COOPERATIVE RENDEZVOUS AND PROXIMITY OPERATIONS FOR ACTIVE DEBRIS REMOVAL MISSIONS

Takahiro Sasaki,[*] Naomi Murakami,[*] Yu Nakajima,[*] Moeko Hidaka,[*] Ryo Nakamura,[†] and Toru Yamamoto[‡]

The amount of orbital debris increases daily, and so does the risk of serious collisions with spacecraft. One approach garnering increased attention is active debris removal (ADR). The first step in a debris removal mission is to approach the debris. In this phase, it is essential to ensure passive abort safety and guarantee robustness against collisions from off-nominal thruster burns, which may be caused by spacecraft anomalies such as failure of navigation sensors or actuators. Linear covariance analysis (LCA) is a powerful method to design safe trajectories that examines a trajectory's applicability with many parameters, while considering calculating cost. This study first addresses a practical rendezvous scenario for an ADR mission. It then proposes LCA with an event trigger function for a spiral approach, a safe trajectory that considers relative orbit elements. Finally, the proposed rendezvous trajectory is shown to be safe from collision with debris, using the proposed LCA method.

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AAS 21-357

OPTIMAL TRAJECTORY CONTROL OF J_2 PERTURBED SPACECRAFT RELATIVE MOTION IN ELLIPTICAL ORBIT

Ayansola D. Ogundele[*] and Olufemi A. Agboola[†]

The proper functioning of aerospace systems and their ability to be able to achieve the mission objectives depend largely on proper understanding of their relative motion dynamics and ability to keep them in the required mission operation configurations through proper control. In real sense, most aerospace systems dynamics are nonlinear and this pose problem for their proper control. In this paper, nonlinear dynamics and control of J_2 perturbed spacecraft formation flying are developed via Euler-Lagrange and State Dependent Riccati Equation (SDRE) approach. J_2 perturbed nonlinear dynamic relative motion model containing quadratic nonlinear terms is obtained from the original nonlinear J_2 perturbed equation. Then, SDRE technique is applied to the model to convert it into a pseudo-linear state-dependent coefficient (SDC) form which is non-unique. The numerical simulations of the four SDC parameterizations developed show that the SDRE controllers are maximally robust and able to return the system to the desired radial, along-track and cross-track positions.

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AAS 21-419

CHALLENGE PROBLEM: ASSURED SATELLITE PROXIMITY OPERATIONS*

Christopher D. Petersen,† Sean Phillips,‡ Kerianne L. Hobbs§ and Kendra Lang**

Assuring safety of a spacecraft during autonomous rendezvous, proximity operations, and docking is a non-trivial, multi-constraint challenge. This paper presents a challenge problem relating to in-plane autonomous rendezvous and docking of a basic 6U CubeSat model with thrust in one axial direction, a reaction wheel for attitude control, and a gimbaled sensor. To assure the safety of the satellite throughout the entire operation, a variety of constraints are introduced with notional values. Moreover, we list several metrics to compare the developed algorithms. Lastly, the benefits and disadvantages for several different solution approaches to the challenge problem are discussed.

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AAS 21-423

AUTONOMOUS SATELLITE RENDEZVOUS AND PROXIMITY OPERATIONS VIA MODEL PREDICTIVE CONTROL METHODS*

Anonto Zaman,† Alexander A. Soderlund,‡ Christopher Petersen,§ and Sean Phillips**

This work examines the autonomous rendezvous, proximity operations, and docking (ARPOD) problem wherein a “chaser” spacecraft with single-axis thrust control and one reaction wheel must maneuver and dock with a “target” spacecraft whilst maintaining safety constraints. The challenge lies in the fact that the chaser satellite is underactuated, and there is coupling in its translational and rotational dynamics. More specifically, in this paper, we consider the case of planar HCW dynamics where the chaser satellite has the capability to thrust in a single axial direction and has a reaction wheel to induce rotation along the ”out-of-plane” direction. As mentioned above, we consider the problem of autonomous achieving a docking configuration with a particular location of the docking port. To drive the inputs of the chaser we leverage a non-linear model predictive control (MPC) methodology in order to construct an efficient control policy while adhering to nonlinear dynamics and constraints (e.g. thrust limits, angular velocity limits, etc.). We provide an in-depth numerical simulation analysis to demonstrate successful and safe docking through this MPC-driven approach.

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AAS 21-438

FORCED RELATIVE MOTION USING THE CLOHESSY-WILTSHIRE EQUATIONS

C1C Brendan Hennessey Rose,* Lt Col (Ret.) Blair F. Thompson,* and Lt Col Daniel J. Showalter*

In this paper we present a novel method for the development and analysis of forced motion relative trajectories between two spacecraft. The method is based on Lambert targeting in the natural relative motion space of the Clohessy-Wiltshire (CW) equations. The desired relative motion trajectory is discretized over time of flight with a cubic spline. The method can then be used to determine the feasibility of the desired relative trajectory compared to the thrust availability for a particular spacecraft, and to modify the trajectory and time of flight to satisfy maneuvering constraints such as line of sight, etc. This method determines the feasibility for specific trajectories including spiral-in, phase matching spiral-in and sun phase matching using the cubic spline model. However, this new method can also test any trajectory and could be integrated into mission planning tools for enhanced proximity operations.

[View Full Paper]

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SATELLITE FORMATION AND COLLISION AVOIDANCE

Session Chair:

Session 4: Christopher Roscoe, Tiger Innovations

The following papers were not available for publication:

AAS 21-313 Paper Withdrawn

AAS 21-440 Paper Withdrawn

AAS 21-267

COLLISION PROBABILITY FOR A GENERAL SPACECRAFT

Ken Chan[*]

This paper deals with the formulation of analytical expressions (up to the fourth order in a Taylor's series expansion of the Gaussian probability density function) for computing the collision probability of a general spacecraft whose cross-section can be described by combinations of circles, ellipses, rectangles, parallelograms and polygons of any shape. These polygons may be convex or concave simply connected or even multiply connected regions. Since any spacecraft cross-section can be decomposed into these elemental cross sections to any degree of accuracy, this formulation will yield the collision probability for an actual collision cross section of an entire spacecraft with space debris. From previous experience, it is expected that the answers are accurate to six or seven decimal digits when terms up to the third or fourth order are retained in the Taylor's Expansion of the Gaussian pdf. This accuracy may be increased by going to higher order terms in the Taylor's series expansion. Finally, this method is extended to the case of any polygonal cross sections for differentiable non-Gaussian pdfs.

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AAS 21-276

DETERMINATION OF EFFICIENT QUANTITIES OF INTEREST FOR SPACE SITUATIONAL AWARENESS AND ADAPTIVE MONTE CARLO

Andrew W. VanFossen[*] and Mrinal Kumar[†]

Space situational awareness (SSA) necessitates accurate uncertainty forecasting for trustworthy conjunction assessment of space assets. This paper concerns an adaptive Monte Carlo forecasting platform designed for uncertainty propagation in nonlinear dynamic systems with guarantees on prediction accuracy of prescribed system quantities of interest (QOIs). This paper investigates two separate QOIs for the purpose of forecasting the probability of collision (P_c) in geostationary orbit: the longitude variation and trace of the state covariance matrix. It is discovered that tracking the trace of the state covariance is 3–10X more computationally efficient than longitude variation. Even so, the ensemble generated from the state covariance can lead to less accurate computations of probability of collision since P_c is not the controlled QoI within the platform.

[View Full Paper]

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AAS 21-311

LOW-THRUST COLLISION AVOIDANCE MANEUVERS USING OPTIMAL CONTROL THEORY AND CONVEX OPTIMIZATION

Carlos Belmonte Hernández,* Álvaro Martínez Chamarro,† and Roberto Armellin‡

This work presents two approaches to compute low-thrust collision avoidance maneuvers for short-term encounters with acceleration control. The first method starts from a minimum-energy optimal control problem. First, a semi-analytic approach based on the linearization of the dynamics is studied. Starting from this continuous solution, a bang-bang structure is achieved by applying a smoothing approach. In the second method, the maneuver design is formulated as a convex optimization problem. The optimization vector consists in the sequence of constant control acceleration applied on the segments in which the trajectory is discretized. In both cases, constraints on either an approximated value of the collision probability, the miss distance, or the maximum collision probability are considered. The two approaches are compared in terms of optimality, efficiency, and robustness using a real conjunction derived from the European Space Agency collision challenge.

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AAS 21-361

STATE-SPACE CONTROLLER FOR LEO, LOW-THRUST SATELLITE CONSTELLATIONS

Mario Melendrez Contreras,[*] David Arnas,[†] and Richard Linares[‡]

Due to the increase in popularity of satellite constellations, some altitudes in LEO have experienced a large increase in number of satellites. This is a trend expected to continue in the future, which could potentially lead to an increased risk of collision between satellites. Collision avoidance is therefore paramount to maintain normal operations and to prevent runaway growth of space debris in LEO. To that end, this work develops a state-space controller for LEO satellites operating in near-circular orbits with low-thrust engines. This is done using a linearized model of the dynamics under the Earth gravitational potential and the atmospheric drag.

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AAS 21-410

OPTIMIZING FORMATION FLYING ORBIT DESIGNS

James Ragan,[*] Razi Ahmed,[†] Kai Matsuka,[‡]
Ilgin Seker,[§] James Walker,[**] Soon-Jo Chung,[††] and Marco Lavalle[‡‡]

We present a method for optimizing the design of a formation flying mission against a science objective, and analyze the orbit design of the NASA Distributed Aperture Radar Tomographic Sensors (DARTS) mission concept. This analysis combines relative orbital motion dynamics, Synthetic Aperture Radar (SAR) tomography science objectives, and a mathematical optimization to create a framework for qualitatively evaluating candidate orbit designs to select an optimal configuration. An optimization problem is constructed, and a genetic algorithm is employed to approximate solutions to the optimal orbit design problem, under the constraints of J_2 invariant relative motion and a minimum allowable SAR signal ambiguity. The resulting formations are then compared to existing SAR formation designs to validate the approach taken.

[View Full Paper]

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AAS 21-417

STRUCTURAL DESIGN AND IMPACT ANALYSIS OF A 1.5U CUBESAT ON THE LUNAR SURFACE

Christopher W. Hays,[*] Daniel Posada,[†] Aryslan Malik,[‡] Dalton Korczyk,[§] Ben Dafoe,[**] and Troy Henderson[††]

Ahead of the United States' crewed return to the moon in 2024, Intuitive Machines, under a NASA Commercial Lunar Payload Services contract, will land their Nova-C lunar lander in October 2021. At 30 meters altitude during the terminal descent, EagleCam will be deployed, and will capture and transmit the first-ever third-person images of a spacecraft making an extraterrestrial landing. This paper will focus on the structural design, modeling, and impact analysis of a 1.5U CubeSat payload to withstand a ballistic, soft-touch landing on the lunar surface.

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ASTEROIDS AND MARS

Session Chairs:

Session 5: Roberto Furfaro, The University of Arizona

Session 19: Anil Rao, University of Florida

SURFACE LOCOMOTION CHARACTERISTICS OF THE SPHERICAL ROVER IN DIFFERENT LOCAL TERRAINS OF ASTEROIDS

Ziwen Li,[*] Tongge Wen,[†] and Xiangyuan Zeng[‡]

Asteroids are in a wide range of landforms according to recent space explorations. The study analyzes the influence of the asteroid complex local terrains on the hopping rovers' trajectory evolution. This paper constructs the local rocky terrains by changing the rock shape and size, reflecting the asteroid's various surface roughness. Cube, icosahedron, and dodecahedron are applied as rocks, respectively, and each rock shape corresponds to three different sizes. Trajectories of the spherical rover with different initial velocity increments are simulated under nine different rocky terrains. The influences of the terrain roughness on the terminal distribution, the collision number, and the transfer distance are analyzed and compared in detail. The critical factors determining the rocky terrain's influence on the multi-trajectory evolutions are finally discussed, such as the initial velocity increment and the rock's shape and size.

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AAS 21-227

HIGH-FIDELITY NATURAL LANDING SIMULATION OF SMALL BODY LANDERS BASED ON POLYGONAL CONTACT

Yonglong Zhang,* Tongge Wen,† Ziwen Li,‡
Xiangyuan Zeng,§ and Junfeng Li**

The surface dynamics of small bodies is a key technology for landing and sample return missions. It is also very meaningful for the research of morphologic evolution of small bodies. However, the surface dynamics of small bodies is a difficult problem. Indeed, the high-fidelity simulations of a lander on and above the surface of a small body is still a big challenge for us. This paper studies arbitrary shaped landers' 6 degrees of freedom simulations in realistic gravity fields computed through the polyhedron shape models with multi-contact. In detail, contacts between landers and small bodies are processed by the Polygonal Contact Model (PCM). Together with orbital and attitude dynamics, the dynamical model of an arbitrary shaped lander's 6 degrees of freedom motion in the neighborhood of a small body is built. A few numerical issues in integration are also solved. Furthermore, two methods are proposed to reduce the computational cost significantly, which makes Monte Carlo type, large number of simulations feasible. As an evaluation of the proposed method, MINERVA-II-1A's motion in the neighborhood of 162173 Ryugu is simulated and discussed.

[View Full Paper]

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AAS 21-245

FLEXIBLE AND SINGLE-IMPULSE TRANSFERS FOR ASTEROID RETRIEVAL USING THE INVARIANT MANIFOLDS OF THE CIRCULAR-RESTRICTED THREE-BODY PROBLEM

Jack Tyler* **and Alexander Wittig†**

Recent studies have used the invariant manifolds of the Circular-Restricted Three-Body Problem to retrieve Near-Earth Objects into Lagrange point orbits of the Sun-Earth system. Objects retrievable below a cost of 500m/s have been classified as Easily Retrievable Objects (EROs). In this work we significantly extend on the previous literature, both in the number of EROs and their optimal solutions: 44 EROs are presented, including four new EROs below 100m/s. We also study the Pareto fronts of the EROs for the first time, demonstrating that the retrieval cost is approximately constant for any transfer time, including single-impulse transfers onto a capture orbit for only marginally higher cost than two-impulse transfers for many EROs.

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AAS 21-296

ASTEROID LANDING WITH A SOLAR SAIL: LANDER DEPLOYMENT

Iain Moore,* Colin R. McInnes,† and Matteo Ceriotti‡

A critical phase of any mission which aims to interact with the surface of an asteroid is in landing. This can be done via landing of the main spacecraft, or by the deployment of separate landers. In this work, the spacecraft will be propelled by a solar sail. The solar sail is capable of delivering high energy missions, given the unlimited momentum available from the Sun. The performance of the sail is dependent on the area to mass ratio of the sail/spacecraft combination. The separation of a significant mass from the main spacecraft will result in a change in performance of the solar sail. This changing performance will affect the dynamics of the solar sail in the near-asteroid environment. This work will investigate the effects of the solar sail in the dynamics of the near asteroid space, as well as the instantaneous change of dynamics at lander separation. Then, work will show the deployment of a lander from various regions of the problem, providing a probability analysis of the success of the lander reaching the surface with a ballistic deployment from each region. Deployment from the region interior to the potential ridge line is found to have the greatest success.

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AAS 21-299

DEIMOS FLYBY OBSERVATION ANALYSIS USING RESONANT FLYBYS FOR THE MMX MISSION

Ferran Gonzalez-Franquesa,* Naoya Ozaki,† and Yasuhiro Kawakatsu‡

Martian Moons eXploration (MMX) is JAXA's next flagship mission. It will be launched in 2024 to visit the moons of Mars, Phobos and Deimos. The mission aims to provide answers on the formation and evolution of the moons and, by extension, the Martian system and the inner Solar System. While the main goal is to observe Phobos and retrieve samples from its surface, the MMX probe will also observe Deimos through a number of flybys. This observation will provide significant additional science, and will allow for close-up visits to regions of Deimos that remain largely unknown. This paper presents recent studies into a resonance-hopping flyby approach currently considered in the MMX mission design. This method allows for observing Deimos during a period of several months while minimizing the impact of the phase on the rest of the mission, enabling periodic encounters between the probe and the moon. Because Deimos is tidally locked with Mars, the surface of the moon that is illuminated at each encounter throughout the phase does not vary significantly. This is addressed by changing the flyby intersection point on Deimos' orbit throughout the phase. The goal of this problem is to maximize the observable illuminated area upon each encounter. This approach provides great flexibility to MMX in terms of targeting multiple specific regions of the moon under varying desired illumination conditions.

[View Full Paper]

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AAS 21-304

OBSERVABILITY-AWARE AND ROBUST TRAJECTORY OPTIMIZATION FOR SMALL-BODY GRAVITY ESTIMATION

Masahiro Fujiwara[*] and Ryu Funase[†]

In small-body explorations, the gravity estimation is the first critical task to design trajectories for main operations and identify some characteristics of the target body. The gravity field can be recovered by tracking the perturbed spacecraft trajectory around the body. To design safe flybys for the gravity estimation even if there are uncertainties of the spacecraft position, velocity, and the gravity field, we propose a robust optimization framework to find the flyby that maximizes the amount of information about the gravity field without impacting. Numerical simulations show the optimal flybys greatly reduce uncertainties of the higher degree and order coefficients.

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AAS 21-336

COMPARING OPTICAL TRACKING TECHNIQUES IN DISTRIBUTED ASTEROID ORBITER MISSIONS USING RAY-TRACING

Kaitlin Dennison[*] and Simone D'Amico[†]

Missions to asteroids have traditionally relied on the Deep Space Network and Light Detection and Ranging (LIDAR) for landmark tracking and mapping. Optical tracking and multi-agent structure from motion show great potential for improving autonomy and reducing hardware requirements in such missions. However, there is a lack of testing and simulation in this area, especially because validation is difficult. In this work, keypoint descriptors are compared to a target-specific landmark descriptor (craters) for optical tracking within a single- and multi-satellite space mission orbiting an asteroid. Additionally, a novel method to validate correlations between any landmark descriptors using ray-tracing is developed. Optical tracking methods are evaluated in simulation to identify tracking limitations. Simulated test cases are validated using the novel ray-tracing technique. The optical tracking methods are further validated using images from the Near Earth Asteroid Rendezvous (NEAR) Shoemaker mission to Eros. Results indicate that SIFT is the most accurate optical tracking technique across monolithic and distributed space system simulations. However, SURF has the most robustness to lighting conditions and produces the most accurate 3D points from stereo-vision. Craters are shown to be an inconsistent landmark detection method, and normalized cross-correlation appears to be largely unreliable for crater correlation. Despite issues with some optical tracking methods, matching ray-traced landmarks shows great potential for optical tracking validation.

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AAS 21-358

STATION KEEPING OF SATELLITES IN AREOSTATIONARY MARS ORBIT USING MODEL PREDICTIVE CONTROL

Robert David Halverson,[*] Avishai Weiss,[†] and Ryan James Caverly[‡]

In this paper, a model predictive control (MPC) station keeping policy is applied to a point-mass spacecraft orbiting Mars in an areostationary orbit. A high-fidelity orbital model is presented, taking into account the significant orbital perturbations caused by Mars' non-Keplerian gravitational potential; gravitational forces due to the presence of the Sun, Phobos, and Deimos; and solar radiation pressure acting on the satellite. An MPC policy is implemented with the control objective of minimizing fuel consumption (Δv) over an entire Earth year while maintaining the satellite within a prescribed station keeping window. Numerical simulation results at a stable longitude demonstrate the ability for MPC to meet the defined control objectives and improve upon the fuel consumption of other station keeping methods in the literature. This study provides a benchmark for the fuel required to perform aerostationary Mars orbit station keeping at a stable longitude.

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AAS 21-378

ON-BOARD SMALL-BODY SEMANTIC SEGMENTATION BASED ON MORPHOLOGICAL FEATURES WITH U-NET

Mattia Pugliatti,* Michele Maestrini,†
Pierluigi di Lizia,‡ and Francesco Topputo§

Small-bodies such as asteroids and comets exhibit great variability in surface morphological features. These are often unknown beforehand but can be exploited for hazard avoidance during landing, autonomous planning of scientific observations, and for navigation purposes. The detection and classification of such features is a laborious task that requires extensive manual work done by experts in the field. This step renders online usage of images unfeasible for these applications. Such limitation could be overcome thanks to the recent advances in the field of neural networks, which allow to recognize features automatically from an acquired image. However, to train such networks, an annotated dataset needs to be generated with care by field experts, thus requiring once again extensive work and human-in-the-loop. In this work, a methodology that exploits an open-source rendering software, ray-tracing masking, and simple image processing techniques is illustrated, which allows to automatize the segmentation process and build up a robust database of labeled features (i.e. background, surface, craters, boulders, and the terminator region) for small-bodies. A procedural code is designed to generate images and their labels over 7 different small-body shapes for a total of 12; 550 images that are used to train a Convolutional Neural Network with a U-Net architecture in the task of semantic segmentation. The performances of the network are then analyzed in 4 different scenarios. First, the network is evaluated on a test set composed of 1; 050 new images belonging to bodies seen during training. Secondly, the network is evaluated on 3; 000 synthetic images from 2 models that have not been encountered in training. Afterward, one of these latter models is tested in a flyby trajectory scenario consisting of 56 images. The results of the first three tests show state of the art performances and the capability of this method to generalize features across synthetic data. Finally, the network's performances are qualitatively assessed with a set of 59 real images from previously flown missions, highlighting the current limits of this approach. These shortcomings suggest possible directions for future improvement, which are discussed in this work.

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AAS 21-411

THE PERTURBATIVE EFFECTS OF GAS DRAG AT ACTIVE COMETS: EQUATIONS OF MOTION FOR THE MEAN ELEMENTS UNDER PERIODIC INVERSE-SQUARE PERTURBATIONS

Mark J. Moretto* **and Jay McMahon†**

This paper derives equations of motion for the mean elements under a general, periodic, inverse-square, perturbing acceleration and applies these equations to a comet-orbiter. Equations of motion for the mean elements are first derived with a perturbing acceleration described by Fourier series in true anomaly. Fourier series in true anomaly are found for spherical harmonics expansions of the perturbing acceleration in the radial, in-track, cross-track (RIC) frame where the perturbing acceleration are being linked to an inertial frame. Additionally, the rotation of a perturbing acceleration described using spherical harmonics expansions in the inertial frame into the RIC frame is demonstrated. Finally, these results are applied to a comet-orbiter with an inertially fixed attitude.

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AAS 21-442

END TO END ASTEROID ISRU USING AN ON-ORBIT CENTRIFUGE

Jekan Thangavelautham,[*] Ravi teja Nallapu,[†] and Erik Asphaug[‡]

Near-Earth Asteroids (NEAs) are known to be diverse in composition and rich in resources. They could potentially be a source of mining for the new space economy. To date, fundamental research on asteroid mining is yet to occur in asteroid-like gravity environments. Some concepts rely on 'bagging' an asteroid inside an inflatable and where the asteroid material undergoes heating to extract water. More conventional methods of mining would require landing and anchoring onto an asteroid. In addition, we need to determine how to continually extract resource material off the surface of a low-gravity body. In this paper, we present a coherent plan to combine several existing component technologies to simulate asteroid surface conditions in space on a low-speed centrifuge laboratory. Using this centrifuge, our development plan will prove the principal feasibility of a bucketwheel excavating mechanism design (1) to access and continuously collect regolith on an asteroid surface using a bucket wheel excavator and (2) provide process technologies to extract water (as a resource). The low gravity and unique surface character of asteroids, which can vary from rocky, metal, or icy surfaces to rubble piles, make landing, mobility, manipulation, and resource utilization a daunting proposition. All of these factors pose a high risk and have resulted in the loss of several asteroids/small bodies exploration spacecraft, including the Hayabusa lander and Phobos mission.

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AAS 21-443

VISUAL RECONNAISSANCE OF TUMBLING ASTEROIDS WITH MOTHER DAUGHTER SWARMS

Ravi teja Nallapu[*] and Jekan Thangavelautham[†]

Asteroid exploration has many potential benefits to planetary science, space security, and the economy. However, it is a challenging task due to the asteroid's low-gravity field and uncertainty in the gravitational environment. Attempting surface missions with inadequate gravity field information is prone to a high risk of failure. Additionally, gravity environments around these bodies constrain the radius of orbiting missions around asteroids. This leaves spacecraft flybys as an alternate, low-cost strategy for reconnaissance. The challenge with flybys is that they are time-limited, thus providing only a limited glimpse of the target. These disadvantages can be overcome using a multi-spacecraft (swarm) approach where a complex task is delegated to multiple-low cost agents to achieve synergistic performance. Our previous research developed IDEAS, an automated software solution to design small body reconnaissance missions using spacecraft swarm flybys. While swarms are an important tool for small body exploration, their mission design is a complex task, and before IDEAS, there was no end-to-end tool for designing spacecraft swarm missions. IDEAS automates the spacecraft, swarm, and trajectory design processes in a mission using Evolutionary Algorithms. The design principles of IDEAS were demonstrated by designing swarm missions that perform spatial and temporal reconnaissance missions to planetary moons and interstellar visitors. This work develops swarm architectures for reconnaissance missions to tumbling asteroids. The design of such missions faces two key challenges. First, the spin axis of these asteroids undergoes complex rotational motion. This dynamic variation, coupled with their irregular shapes, results in large fluctuations in the surface coverage of the swarms. An additional challenge here is that these asteroids tend to have slower rotation periods, which results in longer periods between spacecraft passages, making the mission design process complex and unintuitive. To address these challenges, we present the design of swarm architectures that generate a global surface map of the asteroid from multiple flyby encounters. The swarm is deployed in a mother-daughter architecture, where a mothership deploys the swarm during a designed point on its heliocentric trajectory. We then present stochastic models to evaluate the coverage of the generated surface map. The models are used to formulate the spacecraft, swarm, and trajectory design problems that are handled by the different design modules of IDEAS. The architectures presented in this work are then demonstrated using a case study of a simulated global surface mapping mission to the asteroid 4179 Toutatis, where the number of spacecraft in the swarm is minimized. The results demonstrate our ability to design recon swarms that can fully map an asteroid even under difficult tumbling scenarios.

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AAS 21-444

TETHERED ROBOTIC EXPLORER FOR ACCESSING CLIFFS, CANYONS, AND CRATERS ON THE SURFACE OF MARS

Jekan Thangavelautham,[*] Tristan Schuler,[†] Michael Debbins,[‡] Kairav Kukkala,[§] Viru Vilvanathan,[**] Claire Bukowski,[††] and Himangshu Kalita[‡‡]

Over the past 40 years, robot landers and rovers have explored the surface of Mars. These landers and rovers have carried sophisticated science laboratories and instrumentation that have provided insight into Martian geo-history, particularly ancient times when oceans may have flowed. However, these landers and rovers are unable to reach areas of high-interest such as Valles Marineris, large parts of the Southern Highlands, or the ancient volcanic regions near Olympus Mons. Orbital assets have provided high-resolution imagery of the Martian surface up to 0.3 m/pixel; however, they too are limited from mapping steep canyon/cliff/crater walls. We have proposed the development of secondary payloads such as solar balloons and inflatable sail-planes that would be carried on Mars flagship missions. These secondary payloads could reach these areas of high-interest on Mars and provide high-resolution remote sensing capability, including high-resolution imagery and spectroscopy in search of past and present life. In this paper, we propose augmenting these flying robotic vehicles with a Tethered-Robotic Explorer (TREx) and describing the GNC requirements, challenges, and hardware selection. TREx would be packaged into a 3U CubeSat (34 × 10 × 10 cm3), 4 kg mass, with a tether running through the longitudinal center. TREx would be divided into segments as small as 0.5U that would house specialized instruments, actuators or sensors and independently roll up and down one or more tethers. TREx would rappel down a tether mounted to a sail-plane or solar balloon to anchor the vehicle to a canyon wall or cliff. Once the vehicle is anchored, segments of TREx would move up and down the tether to perform high-resolution 3D LIDAR mapping, obtain surface shavings and rock core samples. The advantage of the proposed TREx robot, thanks to it being lifted by a solar balloon or sail-plane, is that we do not have to be concerned about the robot climbing or mounting to a side wall with the risk of crushing and slipping from grip points. This approach vastly simplifies access to and exploration of cliff/canyon/crater walls compared to many previous methods.

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AAS 21-445

ADVANCING ASTEROID SURFACE MOBILITY USING MACHINE LEARNING AND THE SPIKE SPACECRAFT CONCEPT

Himangshu Kalita,[*] Stephen Schwartz,[†] Erik Asphaug,[‡] and Jekan Thangavelautham[§]

The current generation of asteroid mission such as Hayabusa II and OSIRIS-Rex all perform touch and go operations to minimize the risk of contact with an asteroid surface. This limits the spacecraft from accessing one or two regions on the asteroid surface and prevents these missions from getting diverse representative samples from a rubble pile asteroid. Future missions to asteroids need to overcome this mission limitation and obtain science measurements from multiple points on an asteroid surface. In this paper, we concurrently evolve the design and control of a pair of legs attached to a spacecraft called SPIKE. The spacecraft is inspired by the flamingo, a bird that dwells in coastal muddy surfaces and swamps. The long thin legs enable the flamingo to walk through these precarious surfaces without requires much force. SPIKE needs to operate on rubble pile asteroids surfaces where the gravity is low and the surface precarious. We are already utilizing machine learning methods to evolve suitable walking gaits for SPIKE on nominally flat low-gravity asteroid environment. The legs need to make contact with the asteroid surface material without sinking too far in. In this work, we extend our earlier work to evolve complex leg configurations that can enable a pair of legs to trot, hop in various configurations, and dig into the surface while hoping. The potential for digging into an asteroid surface through modified walking gaits has benefits, particularly in accessing the material underneath that has not been impacted by space weathering.

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LOW THRUST TRAJECTORY

Session Chairs:

Session 6: Natasha Bosanac, University of Colorado, Boulder

Session 11: Arnaud Boutonnet, European Space Agency / ESOC

AAS 21-231

LOW-THRUST TRAJECTORY DESIGN WITH CONVEX OPTIMIZATION FOR LIBRATION POINT ORBITS

Yuki Kayama,[*] Kathleen C. Howell,[†] Mai Bando,[‡] and Shinji Hokamoto[§]

In space missions, numerical techniques for minimizing the fuel consumption of spacecraft using low-thrust propulsion are desirable. Among various nonlinear optimization methods, convex optimization has been attracting attention because it allows optimal solutions to emerge robustly and requires short computation times. In particular, trajectory design in the three-body problem near the Lagrange points involves instability and nonlinearity. Hence, in this study, we consider the application of convex optimization to trajectory design with low-thrust propulsion in cislunar space and verify that this technique performs well, even for sensitive and highly nonlinear dynamics. Specifically, the convex optimization scheme is applied in the transfer from a halo orbit to the near-rectilinear halo orbit which is a periodic orbit defined in the CR3BP. As a further step, the transfer problem is transitioned to an ephemeris model. This investigation provides valuable insight into convex optimization technique in the three-body problem and facilitates the estimation of low-thrust trajectory designs for complex space missions.

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AAS 21-242

FUEL OPTIMIZATION OF LOW-THRUST SATELLITES USING A SEMI-ANALYTIC APPROACH

Axel Garcia,* Richard Linares,† Zach Folcik,‡ Christopher Jewison,§ Paul Cefola,** David Gondelach,†† and Juan F. San-Juan‡‡

The main goal of this research is to optimize low-thrust collision avoidance maneuvers for both the probability-of-collision between satellites and the propellant expenditure considering a J_2 perturbation model. As a first step, an indirect control method integrated with the current DSST software platform is presented in this paper. We apply numerical and semi-analytical propagation techniques to efficiently compute optimal low-thrust trajectories with the goal of risk mitigation in probability-of-collision within a mega-constellation of satellites. Efficiency, accuracy, robustness, and computational speed trades between these propagation techniques are analyzed and discussed in this paper. This research has numerous guidance and control applications for achieving mission success and safety in autonomous operations.

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AAS 21-273

EXPLORATION OF LOW-THRUST LUNAR SWINGBY ESCAPE TRAJECTORIES

Jackson L. Shannon,[*] Donald Ellison,[†] and Christine M. Hartzell[‡]

Spiral escape trajectories can enable a spacecraft to escape Earth's gravity and travel into interplanetary space under its own power. This analysis demonstrates a method for designing spiral escape trajectories that leverages single and double Lunar gravity assists and compares the effectiveness of each trajectory type. The trajectories are constructed by combining backwards propagated Q-Law and a perturbed Sims-Flanagan transcription to design the spiral and interplanetary phases, respectively. We demonstrate that these mission types result in significant propellant savings when compared to a conventional, no Lunar swingby spiral escape, and are highly beneficial for the interplanetary rideshare mission concept.

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AAS 21-302

A HYBRID CLOSED-LOOP GUIDANCE STRATEGY FOR LOW-THRUST SPACECRAFT ENABLED BY NEURAL NETWORKS

Nicholas B. LaFarge,[*] Kathleen C. Howell,[†] and Richard Linares[‡]

Recent advancements demonstrate machine learning as a potentially effective approach for onboard guidance. Neural network controllers overcome challenging dynamical regions of space and, in contrast to traditional iterative approaches, evaluate in constant time. However, neural networks frequently behave unpredictably, and the resulting control solution is likely to violate practical limits. This investigation proposes a hybrid guidance approach that simultaneously benefits from the speed of neural networks and the robustness of traditional iterative methods to ensure all mission criteria are met. In this paradigm, the neural network rapidly produces accurate startup solutions that undergo several pre-processing techniques, ultimately improving the performance for onboard targeting.

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AAS 21-315

AUTONOMOUS GUIDANCE FOR MULTI-REVOLUTION LOW-THRUST ORBIT TRANSFER VIA REINFORCEMENT LEARNING

Hyeokjoon Kwon,[*] Snyoll Oghim,[†] and Hyochoong Bang[‡]

In this paper, we propose low-thrust spacecraft guidance for multi-revolution orbit transfer using the Soft Actor-Critic (SAC) reinforcement learning (RL) algorithm. Assuming the thrust magnitude is constant, the guidance system of a spacecraft must provide the appropriate direction of the thrust at a given state to reach the desired orbit, satisfying mission requirements such as flight time. We built the RL agent that decides the thrust directions over the entire multi-revolution orbit transfer, satisfying the terminal boundary condition and minimizing the flight time simultaneously. The reward function was designed as a gradient form to achieve the efficient training. With the same step size between action changes, the proposed method outperformed the Q-law guidance.

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AAS 21-331

INITIAL MANEUVER TARGETING AROUND SMALL BODIES USING LOW-THRUST PROPULSION

Donald H. Kuettel III[*] and Jay W. McMahon[†]

Low-thrust propulsion is a natural choice for spacecraft propulsion around small bodies. However, the finite, continuous-thrust maneuvers associated with low-thrust propulsion are not able to be accomplished with a traditional open-loop GNC approach. This paper develops an autonomous spacecraft maneuver planning algorithm using a parametric bilinear tangent guidance law. This is accomplished using a two-step approach. First, an optimal impulsive maneuver is calculated. This impulsive maneuver is turned into an initial guess for the bilinear tangent guidance parameters that define the continuous-thrust maneuver. Finally, these guidance parameters are corrected using a Newton-Raphson predictor-corrector to converge on the final continuous-thrust maneuver.

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AAS 21-344

A MODIFIED ORBIT CHAINING FRAMEWORK FOR LOW-THRUST TRANSFERS BETWEEN ORBITS IN CISLUNAR SPACE

Bonnie Prado Pino,[*] Kathleen C. Howell,[†] and David C. Folta[‡]

In an effort to explore further extended mission options for the secondary payload riding along the NASA Artemis-1 spacecraft[1], the Lunar IceCube (LIC) satellite, new interest arises into the problem of constructing a general framework for the initial guess generation of low-thrust trajectories in cislunar space, that is independent of the force models in which the orbits of interest are defined. Given the efficiency of the LIC low-thrust engine[2], after completion of its primary science and technology demonstrations in an orbit around the Moon, the spacecraft could perform further exploration of the cislunar space. In this investigation, a generalized strategy for constructing initial guesses for low-thrust spacecraft traveling between lunar orbits that exist within the context of multiple dynamical models is presented. These trajectories are converged as mass-optimal solutions in lower fidelity model, that are easily transitioned and validated in the higher fidelity ephemeris model, and, achieve large orbital plane changes while evolving entirely within the cislunar region.

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AAS 21-350

TOWARD ON-BOARD GUIDANCE OF LOW-THRUST SPACECRAFT IN DEEP SPACE USING SEQUENTIAL CONVEX PROGRAMMING

Christian Hofmann* and Francesco Topputo†

A robust algorithm to solve the low-thrust fuel-optimal trajectory optimization problem for interplanetary spacecraft is developed in this work. The original nonlinear optimal control problem is convexified and transformed into a parameter optimization problem using the adaptive flipped Radau pseudospectral discretization scheme. The switching times are determined and added as optimization variables in a subsequent optimization process to obtain an accurate on-off control structure. The efficiency of the proposed algorithm is shown in two numerical examples: minimum-fuel transfers from Earth to Venus and Earth to asteroid Dionysus. Simulations are carried out on a desktop computer and a single-board computer. The overall robustness is assessed by varying the quality of the initial guess through a shape-based method and compared to results in the literature and state-of-the-art solvers. The results show a superior performance in terms of computational effort compared to standard nonlinear programming solvers while yielding similar accuracy.

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AAS 21-368

INDIRECT OPTIMIZATION FOR LOW-THRUST TRANSFERS WITH EARTH-SHADOW ECLIPSES

Yang Wang[*] and Francesco Topputo[†]

An efficient indirect method is presented to solve optimal low-thrust Earth-orbit transfers in presence of shadow eclipses. The key feature of our method is the capability to offer accurate gradients of problem functions with respect to all decision variables, which is pivotal for robust convergence. Particular attention is paid to handling the discontinuity conduced by Earth-shadow eclipses. The state transition matrix at shadow entrance and exit is compensated based on calculus of variations. A systematic framework for solving both time-optimal and fuel-optimal problems is established by combining analytic derivatives, switching time detection and two-level continuation with an augmented integration flowchart. The GTO to GEO transfers are simulated to illustrate the effectiveness and efficiency of the method developed.

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AAS 21-369

A NEW METHODOLOGY FOR THE SOLUTION OF THE STIFFNESS PROBLEM APPLIED TO LOW-THRUST TRAJECTORY OPTIMISATION IN TERMS OF ORBITAL ELEMENTS USING DIFFERENTIAL DYNAMIC PROGRAMMING

Marco Nugnes[*] and Camilla Colombo[†]

The largest part of direct and indirect methods for trajectory optimisation exploits Cartesian coordinates as state representation of the dynamical systems. However, for specific dynamical systems such as orbit dynamics, orbital elements represent an attractive alternative because they provide a physical insight into the time evolution of the orbit geometry. The use of the orbital elements though makes the dynamical system stiff because of the different time evolution between fast and slow variables. This paper proposes a solution to the stiffness problem for the low-thrust trajectory optimisation using orbital elements as state representation and the Differential Dynamics Programming as optimization method.

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AAS 21-374

LOW-THRUST TRAJECTORY OPTIMIZATION USING THE KUSTAANHEIMO-STIEFEL TRANSFORMATION

Kevin Tracy* and Zachary Manchester*

We present a novel trajectory optimization formulation for the low-thrust orbital transfer problem utilizing the Kustaanheimo-Stiefel transformation. For unperturbed two-body motion, this transformation maps the nonlinear Cartesian dynamics to a linear four-dimensional simple-harmonic oscillator. When perturbing accelerations are added, the dynamics become nonlinear, but are significantly better approximated by linearization than alternative state representations. Therefore, the Kustaanheimo-Stiefel dynamics have strong advantages in gradient or Newton-based trajectory optimization algorithms. We formulate a low-thrust trajectory optimization problem with these dynamics and demonstrate empirically that thrust profiles can be found without providing an initial guess to the solver, and with fewer knot points than alternative state representations.

[View Full Paper]

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AAS 21-384

LOW-THRUST TRANSFER TRAJECTORIES TO EARTH-MOON NEAR RECTILINEAR HALO ORBITS

Emmanuel Blazquez,[*] Alberto Fossà,[†] Tom Semblanet,[‡] and Stéphanie Lizy-Destrez[§]

Low-thrust propulsion is a promising technology for station-keeping maneuvers and fuel-efficient cargo delivery to the Gateway. This work proposes new methodologies to design fuel-optimal low-thrust propulsion transfers to EML-2 Near Rectilinear Halo Orbits (NRHOs) from Low Earth Orbits and other Earth-Moon NRHOs. Trajectories are computed as solutions of continuous-time optimal control problems, minimizing the propellant mass consumption. The paper introduces a novel trajectory stacking procedure to generate initial guesses for the optimization problem, patching together segments of carefully selected trajectories in the vicinity of the departure and arrival orbits. This initialization, easily automatized, converges towards fuel-efficient transfers with reduced time of flight.

[View Full Paper]

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AAS 21-385

COMPARISON OF COSTATE INITIALIZATION TECHNIQUES FOR FUEL-OPTIMAL LOW-THRUST TRAJECTORY DESIGN

Praveen J. Ayyanathan[*] and Ehsan Taheri[†]

In this paper, two methodologies are investigated for generating the missing initial costate values of the Hamiltonian boundary-value problems associated with minimum-fuel low-thrust trajectories. Specifically, the set of Cartesian coordinates and Modified Equinoctial Elements (MEEs) are used for modeling dynamics. The initial costates are obtained using two methods: 1) random initialization, and 2) when costate initial values are constrained to lie on a unit 8-dimensional hypersphere. Minimum-fuel trajectories are designed for a heliocentric maneuver from Earth to comet 67P/Churyumov–Gerasimenko. The two costate initialization methods are compared against each other in terms of the percent of convergence and accuracy of the results of the associated boundary-value problems.

[View Full Paper]

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HYBRID EVOLUTIONARY-INDIRECT MULTIPLE-GRAVITY-ASSIST LOW-THRUST INTERPLANETARY TRAJECTORY DESIGN

Nicholas P. Nurre[*] and Ehsan Taheri[†]

In this work, an enhanced indirect optimization method is implemented as the inner-level solver within a hybrid evolutionary-indirect dual-level algorithm. The input to the algorithm is a user-defined sequence of planets. The outer-level optimization algorithm, a particle swarm optimization algorithm, optimizes over boundary conditions, time of phases, and gravity-assist parameters. The innerlevel solver finds a fuel-optimal trajectory for each segment of the trajectory by solving a Hamiltonian two-point boundary-value problem. The proposed duallevel hybrid algorithm is capable of finding candidate optimal trajectories for interplanetary missions with forced coast arcs immediately after launch and before and after each gravity-assist maneuver. Application of the proposed algorithm is demonstrated by solving two problems with multiple gravity-assist maneuvers.

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AAS 21-422

REACHABLE SET OF LOW DELTA-V TRAJECTORIES FOLLOWING A GRAVITY-ASSIST FLYBY

Chun-Yi Wu* and Ryan P. Russell†

Planetary moons flyby tours are challenging to design due to the extraordinarily large search space. State-of-the-practice approaches rely on discretized grid searches over a reduced domain, and often waste computation on solutions with excessively high delta-v. A new method is proposed that (a) considers the full domain of reachable bodies and transfer types including even-npi, odd-npi, non-resonant ballistic, and v-infinity leveraging, (b) identifies families of solutions instead of just single points, and (c) structures the search to only find solutions within a delta-v threshold. This new approach is designed to rapidly inform an outer-loop pathfinding scheme. Detailed examples of resulting solutions and families are provided for multiple variations of three different use case scenarios, including tours in the Jupiter, Saturn, and Sun systems. As a representative example in the Jupiter system starting at Callisto, the algorithm takes on the order of 0.1 seconds to find and report over 500 solutions organized into nearly seventy families, all either returning to Callisto or proceeding to Ganymede with a delta-v cost of less than 200 m/s.

[View Full Paper]

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ATTITUDE DYNAMICS AND CONTROL

Session Chair:

Session 7: Andrew J. Sinclair, Air Force Research Laboratory

DESIGN OF TIME-OPTIMAL SLEW MANEUVERS WITH BOOLEAN STAR TRACKER AVAILABILITY CONSTRAINTS

Elliott VonWeller,* Mark Karpenko,† and Ronald J. Proulx‡

Path constraints in continuous-time optimal control problems must currently be satisfied as a set of logical conjunctions. In many applications, constraints may contain non-conjunction operators. This paper explores attitude maneuver designs in which at least one of two star tracker must remain always unocculted by bright objects. The usual AND constraint is relaxed in favor of a negated-conjunction (NAND), or Sheffer stroke, path constraint when developing solutions for time-optimal slews. This solution embeds a continuous representation of the discrete logic as part of the optimal control problem formulation. An analysis of the necessary conditions for optimality is developed.

[View Full Paper]

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AAS 21-371

NEUROADAPTIVE OBSERVER DESIGN FOR ATTITUDE SYNCHRONIZATION OF FORMATION-FLYING SPACECRAFT

Garba Subedi[*] and Atri Dutta[†]

This paper considers the problem of attitude synchronization of formation-flying spacecraft in a leaderless network, in the presence of communication delay, external disturbance torque, and system uncertainties. We model the communication network using graph theory and consider an inverse control framework for the tracking of attitude-synchronizing reference attitude and angular velocity. We propose a neuro-adaptive observer that combines the ideas of modified state observer with Chebyshev neural network for estimating unmodeled uncertainties. Numerical simulations are presented to demonstrate the performance of the controller and also to compare with the modified state observer from the literature.

[View Full Paper]

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AAS 21-387

EXAMINATION OF MAGNETIC DIRECTIONAL CONTROL BY FORCE USING SUPERCONDUCTING DIAMAGNETIC EFFECT

Shogo Tochimoto,[*] Takuma Shibata,[†] and Shinichiro Sakai[‡]

For the next- generation space telescope, it is important to suppress the internal vibration and heat from transferring to the observation device. Therefore, we propose "a micro-vibration disturbance suppression mechanism using superconducting magnetic flux pinning effect" In this research the directional control of the mission part was examined. In order to introduce the control, the characteristics of the diamagnetic force was investigated by modeling it and compared with actual measurements. And we also implemented a distance control with diamagnetic force and designed a suitable control for this mechanism. From the experiments, we were able to understand the characteristics of the diamagnetic force and design a controller suitable for the mechanism.

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AAS 21-409

ATTITUDE STATE UNCERTAINTY PROPAGATION USING STOCHASTIC EXPANSIONS

Brandon A. Jones[*] and Trevor Wolf[†]

This paper presents an approach to propagating attitude uncertainty when the state is parameterized using a quaternion with a probability density function defined on the four-dimensional sphere. Using stochastic expansions, such as polynomial chaos expansions, in this context require orthogonal functions to satisfy proofs of convergence. To generate the basis functions, we first evaluate hyperspherical harmonics and apply a numeric orthogonalization procedure. This procedure requires approximation of moments of the harmonics with respect to the initial density, with accuracy of the basis determined by the quality of the moments. Performance of the approach is demonstrated for torque-free and torqued rigid-body motion.

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NAVIGATION

Session Chairs:

Session 8: Brian Gunter, Georgia Institute of Technology

AAS 21-211

THE EVOLUTION OF DEEP SPACE NAVIGATION: 2014-2016*

Lincoln J. Wood†

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 the scientific objectives of the missions and as enabled by improvements in technology. This paper is the eighth in a chronological sequence dealing with the evolution of deep space navigation. The time interval covered extends from 2014 to 2016. 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 11 planetary missions.

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AAS 21-254

SPACECRAFT TERRAIN RELATIVE NAVIGATION WITH SYNTHETIC APERTURE RADAR

Bryan S. Pogorelsky,[*] Renato Zanetti,[†] Jingyi Chen,[‡] and Scott Jenkins[§]

Situations can arise when a spacecraft cannot rely on external signals for navigation and must use onboard instruments to determine its position, velocity, and attitude in orbit. A spacecraft terrain relative navigation system is presented relying on measurements obtained from a synthetic aperture radar that are fused with inertial measurements and attitude determination system data in a multiplicative extended Kalman filter. The method of processing the SAR images to retrieve measurements for the navigation filter is shown, including autofocusing and image geolocation steps. Monte Carlo simulation results are presented in which actual filter performance is compared to predicted filter performance. Specifically, two test cases, with varied initial SAR antenna misalignment uncertainty, demonstrate that the SAR based terrain relative navigation system produces consistent state estimates and successfully bounds, or in some instances, significantly reduces the navigation uncertainty of the spacecraft throughout its trajectory by up to 98%.

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AAS 21-266

NONLINEAR FILTERING WITH INTRINSIC FAULT RESISTANCE

Gunner S. Fritsch[*] and Kyle J. DeMars[†]

Due to limitations in onboard computing, spaceflight navigation has long been relegated to estimation processes that promote computational efficiency over increased model accuracy. Such is the case with fault tolerance methods, where residual editing is the most common practice to screen out erroneous sensor data. This work investigates an alternative approach, where sensor returns classified as faulty are not simply rejected, but are accounted for within the measurement model of the sensor, ultimately leading to a filter with intrinsic fault resistance instead of ad hoc extensions like residual editing. Several different faulty measurement models are examined by comparing the proposed filter to a baseline filter outfitted with residual editing, where analysis is performed to test relative performance, robustness, and approximation ability of the proposed filter, and it is found that the proposed approach outperforms residual editing in all cases.

[View Full Paper]

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AAS 21-298

POSITION ESTIMATION METHOD BY ASTEROID SHAPE IMAGES AND IMAGE CODING METHOD FOR ON-BOARD OPTICAL NAVIGATION

Shuya Kashioka,* Genki Ohira,† Yuki Takao,‡ Taketoshi Iyota,§ and Yuichi Tsuda**

This paper describes a method for estimating the position of a spacecraft by image processing using the point cloud of asteroids. Image navigation is one of the most important techniques for guiding a spacecraft in the vicinity of a target object. However, it is difficult to estimate the position of a spacecraft when the asteroid is far away from the target, or when the asteroid is in shade or shadow. In this paper, we describe an image matching method that can robustly estimate the position of an asteroid by selecting a sunlit region from its contour. The images used for the image processing are the images taken by the spacecraft and the binary images created onboard from the point cloud model of the asteroid. In addition, based on the asteroid-sun geometric relationship, a mask image is created to exclude the shaded points from the asteroid point cloud from the image matching. Using these three types of images, we estimate the position of the asteroid using only the region in the image that is certain to be the contour of the asteroid.

[View Full Paper]

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AAS 21-321

GAUSSIAN MIXTURE PARTICLE FLOW MODELING USING INFORMATION POTENTIAL

Kari C. Ward[*] and Kyle J. DeMars[†]

Recursive filtering methodologies typically require some form of model or assumption to define the underlying probability density function (pdf) associated with the estimated states. One such recursive filter family, known as particle flow, also introduces a kind of update dynamics model to describe the evolution of the pdf over the course of an update. However, in many practical applications, the appropriateness of the particle flow filter is constrained by previous assumptions made about the pdf. This work implements a Gaussian mixture model for the pdf to facilitate accurate estimation using the particle flow framework for non-Gaussian densities and builds upon previous particle flow filter developments that leverage the incorporation of new information to define the flow model. By modeling changes in component interactions during the update using information potential, the information-based particle flow filter can be expanded to address more challenging estimation problems. The resulting filter is compared to the Gaussian mixture extended Kalman filter in a simulation with measurement noise modeled by a Gaussian mixture to examine distribution modeling characteristics.

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RELATIVE NAVIGATION USING A PLANET'S ILLUMINATION CONDITIONS

Kalani Danas Rivera[*] and Mason Pecky[†]

The observed illuminated phases of a planet are used for onboard estimation of the planet-sun unit vector. Onboard optical instruments also provide the spacecraft with unit vectors to the sun and planet. The relative spacecraft-planetary body-sun position and orientation are estimated from these unit vectors. This paper addresses the singularities and limitations of a closed-form estimation process. The proposed relative navigation technology is promising for spacecraft operating in cislunar space and without access to Earth ranging capabilities.

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AAS 21-383

NAVIGATION ABOUT IRREGULAR BODIES THROUGH SEGMENTATION MAPS

Mattia Pugliatti[*] and Francesco Topputo[†]

Optical navigation about small-bodies can be performed at different scales and with different techniques during proximity operations. Traditional methods however are influenced by pixel intensity due to illumination conditions and often provide a navigation solution only when coupled with filtering techniques. In this work, a navigation method for small-body applications is presented that makes use of segmentation maps. By converting a grayscale image into its segmented equivalent the pixel content is highly reduced but at the same time its meaning is enriched since the pixel value is providing direct information on feature type and distribution across space. This is exploited in an autonomous navigation method in two steps. A Convolutional Neural Network is designed to generate a rough estimate of the position of a spacecraft in a small-body fixed reference frame, whose surrounding has been divided into 1176 classes. A Normalized Cross-Correlation technique is then applied to the reduced search space to generate a precise position estimate. The methodology proposed is trained and validated on a database of segmented synthetic maps of 49716 samples of Didymos and Hartley each, while a series of 5 scenarios are tested. The CNN is capable to predict the correct class with an accuracy of 75:94% and 68:60% respectively for Didymos and Hartley, while the overwhelming majority of the other cases are predicted just next to the correct classes. The CNN is robust to various illumination conditions, is capable to work outside the range of distances considered during training, performs well when predicted masks are used, and also selects independently the type of features to rely on for classification depending on the body. When coupled with NCC, a position estimate with a relative error below 5 – 8% the range from the asteroid can be achieved.

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AAS 21-413

NAVIGATION AT ACTIVE COMETS: THE TIME VARYING AND STOCHASTIC COMA

Mark J. Moretto[*] and Jay McMahon[†]

Spacecraft orbiting active comets are subject to a number of perturbing forces including non-spherical gravity, solar radiation pressure, third-body effects, and drag from the coma. Estimation of the spacecraft state is complicated by the fact that the coma is time varying and the parameters related to coma drag are highly uncertain. The coma varies stochastically and periodically, with daily, seasonal, and orbital timescales, and multi-orbit variations. This is a challenge to spacecraft navigators. This paper discusses several approaches to estimating time varying coma properties, piecewise batch and functional approximations. Additionally, lower limits for variation magnitude and duration are explored.

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ATMOSPHERIC REENTRY GUIDANCE AND CONTROL

Session Chairs:

Session 9: Kamesh Subbarao, University of Texas at Arlington

The following paper was not available for publication:

AAS 21-400 Paper Withdrawn

AAS 21-201

NUMERICAL PREDICTOR-CORRECTOR BASED GUIDANCE SCHEME FOR AERO-GRAVITY ASSIST AT TITAN FOR ENCELADUS MISSIONS

Daniel L. Engel,[*] Soumyo Dutta,[†] and Zachary R. Putnam[‡]

Aero-gravity assist is a spacecraft maneuver than can enable a vehicle to insert into an orbit of one planetary body using the atmosphere and gravity field of a secondary body, reducing the required propellant mass relative to a fully-propulsive orbit insertion. The Fully Numerical Predictor-Corrector Aerocapture Guidance algorithm was modified to work with a direct force control blunt body vehicle, executing an aero-gravity assist at Titan to enter a Saturnian orbit and conduct fly-by at Enceladus. Additionally, a proportional-integral-derivative controller was implemented to command sideslip angles for control of the orbital inclination. Numerical simulation showed the developed guidance scheme was capable of minimizing the energy and inclination error at atmospheric exit, allowing Saturnian moon tour trajectories and Enceladus exploration at a small delta-V cost, on the order of 100 m/s in the nominal case.

[View Full Paper]

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AAS 21-202

FLIGHT CONTROL METHODOLOGIES FOR NEPTUNE AEROCAPTURE TRAJECTORIES

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

In this work, a comparison of potential flight control methodologies for Neptune aerocapture trajectories are presented. Lifting trajectories pertaining to bank angle modulation and direct force control as well as ballistic trajectories pertaining to continuously-variable drag modulation are investigated. A parametric study of vehicle configurations is explored to quantitatively compare the flight envelope between lifting and ballistic trajectories. A closed-loop numerical predictor-corrector aerocapture guidance architecture is utilized to unify each flight control technique for trajectory comparisons. A series of Monte Carlo simulations of blunt body Neptune aerocapture trajectories are conducted to assess each flight control's robustness to uncertainties in vehicle aerodynamics, atmospheric knowledge, and entry state. Direct force control can achieve 100% successful science orbit insertion within a 120 m/s total ΔV budget. Bank angle modulation can achieve 100% successful science orbit insertion within a 300 m/s total ΔV budget. Continuously-variable drag modulation can achieve 99.3% successful science orbit insertion within a 190 m/s total ΔV budget but at 3 times lower peak stagnation point convective heating rate.

[View Full Paper]

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AAS 21-306

NONLINEAR SET-MEMBERSHIP FILTERING-BASED STATE ESTIMATION OF REENTRY VEHICLES

Diganta Bhattacharjee[*] and Kamesh Subbarao[†]

In this paper, we propose a nonlinear set-membership filtering-based state estimation technique for reentry vehicles. The recursive set-membership filter utilizes the state dependent coefficient parameterization to acquire a pseudo-linear description of the governing nonlinear system. At every recursion, the filter requires solutions to two convex optimization problems and these solutions can be efficiently obtained. We have included details of the filter design, the nonlinear motion model for the reentry vehicle, and the nonlinear measurement model. A simulation example is included to illustrate the effectiveness of the proposed approach.

[View Full Paper]

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AAS 21-308

ANALYTICAL GUIDANCE FOR MARS AEROCAPTURE VIA DRAG MODULATION

Ibrahim H. Cihan[*] and Craig A. Kluever[†]

Aerocapture is an effective maneuver to insert a spacecraft from a higher-energy orbit into a lower-energy orbit and then enter a target orbit in an economical way. A new analytical predictor-corrector guidance algorithm has been developed for the Mars aerocapture problem. This paper presents a drag-modulation flight control algorithm. Ballistic coefficient controls the vehicle during the atmospheric flight. Velocity during the aerocapture maneuver is modeled by a hyperbolic tangent function of flight-path angle. This formulation results in a closed-loop control law for ballistic coefficient. Guidance periodically updates the velocity profile so that the correct exit conditions are achieved. The corrector utilizes the ratio of the measured drag acceleration (by the vehicle's onboard sensors) to the reference drag acceleration computed by the predictor. Two different apoapsis-targeting scenarios for Mars aerocapture are investigated in this paper. Monte-Carlo simulations are run to demonstrate the performance and robustness of the proposed algorithm. The numerical results of this proposed guidance method are compared with the results from two existing analytical predictor-corrector guidance algorithm.

[View Full Paper]

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ARTIFICIAL INTELLIGENCE IN ASTRODYNAMICS

Session Chairs:

Session 10: Peter Lai, LinQuest Corporation

AAS 21-216

DESIGNING IMPULSIVE STATION-KEEPING MANEUVERS NEAR A SUN-EARTH L2 HALO ORBIT VIA REINFORCEMENT LEARNING

Stefano Bonasera,* Ian Elliott,* Christopher J. Sullivan,*
Natasha Bosanac,† Nisar Ahmed,‡ and Jay McMahon†

Reinforcement learning is used to plan station-keeping maneuvers for a spacecraft operating near a Sun-Earth L2 halo orbit and subject to perturbations from momentum unloads. This scenario is translated into a reinforcement learning problem that reflects the desired goals, variables and dynamical environment. Proximal Policy Optimization is used to train policies that generate station-keeping maneuvers in the circular restricted three-body problem and a point mass ephemeris model. These policies successfully produce bounded trajectories with small maneuver requirements, motivating further development of autonomous maneuver planning technologies for spacecraft operating in complex gravitational environments.

[View Full Paper]

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AAS 21-241

DEEP LEARNING HSGP4: HYPERPARAMETERS ANALYSIS

Edna Segura,[*] Hans Carrillo,[†] Rosario López,[‡] Iván Pérez,[§] Montserrat San-Martín,[**] and Juan F. San-Juan[††]

The hybrid orbit propagation methodology is used to model the error of any type of orbit propagator with the aim of improving its perturbation model or integration technique and hence enhancing its accuracy. In this work, we present an application of the hybrid methodology, in which the time-series forecasting process is performed using deep learning method to SGP4. We have adjusted the resulting Hybrid SGP4 propagator, HSGP4, to the case of Galileo-type orbits. We will describe the hyper-parameter selection, which is an important part of the development of HSGP4, and show how HSGP4 can improve the accuracy of SGP4.

[View Full Paper]

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IMAGE-BASED LUNAR LANDING HAZARD DETECTION VIA DEEP LEARNING

Luca Ghilardi,[*] Andrea D'Ambrosio,[†] Andrea Scorsoglio,[‡] Roberto Furfaro,[§] and Fabio Curti[**]

As part of NASA's Vision for Space Exploration program, future human missions to the moon will require an increased automation level. In particular, it will be essential to perform safe landing autonomously in the presence of hazards. This work deals with an image-based hazard detection for 6DOF (Degrees of Freedom) lunar landing. The proposed approach relies on the new deep learning semantic segmentation for image classification. Images are rendered using a detailed Digital Terrain Model (DTM) from which terrain features are extracted at different illumination conditions. Results show good accuracy for both training and test sets.

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AAS 21-253

UNCERTAINTY-AWARE DEEP LEARNING FOR SAFE LANDING SITE SELECTION

Katherine A. Skinner,[*] Kento Tomita,[†] and Koki Ho[‡]

Hazard detection is critical for enabling autonomous landing on planetary surfaces. Current state-of-the-art methods leverage traditional computer vision approaches to automate identification of safe terrain from input digital elevation models (DEMs). However, performance for these methods can degrade for input DEMs with increased sensor noise. Alternatively, deep learning has been shown to outperform traditional approaches for hazard detection on noisy DEMs. Estimating network uncertainty can provide further insight regarding reliability of network output. This work proposes an uncertainty-aware learning-based method for hazard detection. This paper develops an algorithm to take network predictions and uncertainty maps to produce uncertainty-aware safety maps for landing. Experiments are presented with simulated data with realistic terrain features and varying noise levels to validate the proposed approach.

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AAS 21-381

THE APPLICATION OF STREAMING CLUSTERING TO SPACECRAFT IDENTIFICATION AND TRACKING IN FORMATION AND SWARM MISSIONS

Jill C. Davis[*] and Henry J. Pernicka[†]

The continued development of small satellites has made them an increasingly viable mission alternative to traditional monolithic spacecraft. Constellations, swarms, and formations of these small spacecraft have the potential to fill unique gaps in the space systems architecture, while reducing overall mission costs and increasing mission redundancy. However, cooperative navigation between spacecraft within swarms and formations is critical to mission success, but poses many challenges for SmallSats due to their SWaP constraints. While Earth orbiting missions can rely on GNSS data for high-accuracy inertial and relative navigation, deep space missions will require new navigation techniques. In this work, the swarm/formation navigation problem is divided into two parts: spacecraft identification/data association and relative pose estimation. This research presents a solution to the spacecraft identification and data association problem by using an unsupervised learning (clustering) architecture that classifies spacecraft from monocular camera images. The algorithm presented detects objects in the camera field of view, and then continues to track detected objects over time by classifying incoming data to the correct spacecraft cluster. Simulations were performed using Analytical Graphics Inc. STK software with a swarm of six spacecraft deployed in a lunar orbit. Results show high levels of classification accuracy as well as the ability of the algorithm to adapt as the swarm configuration changes throughout the simulation. The algorithm is also shown to be robust to missing measurements. An incremental cluster validity index was used to quantify the performance of the clustering algorithm. The resulting index value supports the qualitative data indicating that the algorithm correctly identifies and detects new spacecraft.

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AAS 21-393

APPLICATIONS OF PHYSICS-INFORMED NEURAL NETWORKS FOR GRAVITY FIELD MODELING

J. R. Martin* and H. Schaub†

Accurate and computationally efficient dynamics are paramount for high-accuracy astrodynamics simulation and spacecraft control. To yield such dynamics, researchers need high-fidelity representations of the gravitational potential from which trajectories are propagated. Traditionally these representations are constructed analytically using spherical harmonics, mascons, or polyhedrons, and accelerations are then computed by taking the gradient of the potential function. While these representations are convenient for theory, they each come with unique disadvantages in application. Broadly speaking, analytic representations are often not compact, requiring thousands or millions of parameters to adequately model high-order features in the environment. In some cases, analytic models can also be operationally limiting – diverging near the surface of a body. Moreover, these representations can expensive to regress, requiring large volumes of carefully distributed data which may not be readily available in new environments. To combat these challenges, this paper aims to shift the discussion of potential representations away from pure analytic models and towards machine learning models. Within the past decade alone there have been dramatic advances in the field of deep learning which may help to bypass some of the limitations inherit to the analytics of existing gravity models. Specifically, this paper investigates the use of a recent type of neural network, Physics-Informed Neural Network (PINN), to represent the gravitational potential of a celestial body and predict consequent dynamics. The findings presented suggest that these neural network representations can offer advantages over their analytic counterparts in model compactness, regressive ability, and computation speed.

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AAS 21-424

ARTIFICIAL NEURAL NETWORK BASED PREDICTION OF SOLAR ARRAY DEGRADATION DURING ELECTRIC ORBIT-RAISING

Tanzimul H. Farabi[*] and Atri Dutta[†]

This paper presents an artificial neural network based approach for predicting the power loss of all-electric satellites during low-thrust orbit-raising through the Van Allen radiation belts. The developed network can be beneficial in computing thrust availability of the satellite within low-thrust mission design tools that compute the geocentric electric orbit-raising trajectory for the satellite. The neural network is trained on data generated using the AE9/AP9 models for radiation flux calculation and the Space Environment Information System (SPENVIS) for power loss computation. Finally, the application of the network to a sequential low-thrust orbit-raising solver is demonstrated through numerical simulations for orbit-raising starting from a variety of geosynchronous transfer orbits.

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TRAJECTORY DESIGN

Session Chairs:

Session 12: James Thorne, Institute for Defense Analyses (IDA)

Session 16: Powtawche Valerino, NASA Marshall Space Flight Center

Session 26: Rohan Sood, The University of Alabama

AAS 21-221

INVARIANT FUNNELS FOR RESONANT LANDING ORBITS

Jared T. Blanchard,* Martin W. Lo,† Damon Landau,‡ Brian D. Anderson,§ and Sigrid Close**

We discovered a simple, two-part solution to the problem of finding resonant orbits to land on high latitudes of Ocean Worlds. First, we apply a standard planar Poincaré map in the spatial problem to identify a resonant landing orbit. Next we generate an "invariant funnel" of trajectories that converge to the orbit, which acts as an attractor. The funnel has a wide mouth, thousands of kilometers wide, that shrinks to a small disc at a landing site only a few kilometers (or less) wide. These funnels are governed by "resonant rings" of landing trajectories, and will make navigation more simple and robust.

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AAS 21-229

AEROCAPTURE TRAJECTORIES FOR EARTH ORBIT TECHNOLOGY DEMONSTRATION AND ORBITER SCIENCE MISSIONS AT VENUS, MARS, AND NEPTUNE

Bill Strauss,[*] Alex Austin,[†]
Adam Nelessen, Marcus Lobbia, Aaron Schutte, Josh Ravich,
Liz Luthman, Brian Kennedy, Damon Landau, and Matt Jadusingh[‡]

The use of aerocapture to provide the delta-V needed to capture a spacecraft into orbit can provide significant fuel savings compared to a propulsive orbit insertion. The aerocapture guidance method described in this paper uses drag modulation, which deploys a drag skirt in the atmosphere until the amount of delta-V needed to capture into the desired orbit is obtained, at which time the drag skirt is separated from the spacecraft. By modulating the time of drag skirt jettison, the vehicle can target a specific orbit apoapsis in the presence of uncertainties such as entry targeting errors and unknown atmospheric conditions.

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AAS 21-232

EXPECTED THRUST FRACTION: RESILIENT TRAJECTORY DESIGN APPLIED TO THE EARTH RETURN ORBITER

Ari Rubinsztejn,[*] Rohan Sood,[†] and Frank E. Laipert[‡]

Electric propulsion is an enabling technology for the Mars Sample Return campaign being planned by NASA and ESA that affords an order of magnitude reduction in fuel. Unfortunately, electric propulsion's low-thrust capabilities require long thrusting arcs that make spacecraft susceptible to disturbances resulting in missed thrust events. One method for designing trajectories resilient to such missed thrust events is expected thrust fraction, which embeds their stochastic nature into a time-varying duty cycle. This paper investigates the application of expected thrust fraction to the Earth Return Orbiter's outbound Earth-to-Mars trajectory and compares it with trajectories designed using traditional methods to mitigate missed thrust events. Through the use of expected thrust fraction, a trajectory with a baseline 65.4% success rate is improved to an 86.6% success rate. Additionally, when expected thrust fraction is used in conjunction with a terminal coast, a 96.0% success rate is achieved, at the cost of only a 12 kg reduction in delivered mass, which is higher than any single mitigation technique.

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AAS 21-234

EXPLORATION OF DEIMOS AND PHOBOS LEVERAGING RESONANT ORBITS

David Canales,[*] Maaninee Gupta,[†] Beom Park,[‡] and Kathleen C. Howell[§]

While the interest in future missions devoted to Phobos and Deimos increases, missions that explore both moons are expensive in terms of maneuver capabilities partly due to low-energy transfer options that may not be readily available. The proposed approach in this investigation includes Mars-Deimos resonant orbits that offer repeated Deimos flybys as well as access to libration point orbits in the Phobos vicinity. A strategy to select the candidate orbits is discussed and associated costs are analyzed, both for impulsive and low-thrust propulsion capabilities, within the context of the coupled spatial circular restricted three body problem. The trajectory concepts are then validated in a higher-fidelity ephemeris model.

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AAS 21-243

A RAPID TARGET-SEARCH TECHNIQUE FOR KBO EXPLORATION TRAJECTORIES

Miguel Benayas Penas,[*] Kyle M. Hughes,[†] Bruno V. Sarli,[‡] Donald H. Ellison,[§] and Kevin J. Cowan[**]

A rapid, grid-based, target-search algorithm is presented to find candidate sequences of small-body encounters for mission design. The algorithm is especially relevant for cases with large combinatorial spaces. In this paper, the algorithm is used to identify candidate flyby sequences of multiple Kuiper-Belt Objects (KBOs). Before reaching the first KBO in the sequence, the trajectories in this paper first use gravity assists at one or more of the giant planets to pump-up their orbital energy—reducing launch C_3. The target-search algorithm consists of four sequential steps: (1) parameter definition, (2) fine-tuned Lambert-based grid search of ballistic trajectories visiting one KBO, (3) rapid, ΔV -based proximity search for additional KBOs using the state transition matrices (STMs), and (4) trajectory optimization of the most promising KBO sequences using the Evolutionary Mission Trajectory Generator (EMTG). The paper also defines an empirical-based process to characterize the maximum step size for the target arrival dates in the Lambert grid search. Lastly, a candidate mission to two KBOs is presented. The results indicate that the ΔV computed from the STM propagations is not representative of the final ΔV computed in EMTG; however, it does serve as a useful 'reachability' metric to identify nearby KBOs.

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AAS 21-251

MISSION ANALYSIS AND DESIGN OF VMMO: THE VOLATILE MINERALOGY MAPPING ORBITER

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Water ice and other volatile compounds found in permanently shadowed regions near the lunar poles have attracted the interests of space agencies and private companies due to their great potential for in-situ resource utilization and scientific breakthroughs. This paper presents the mission design and trade-off analyses of the Volatile Mineralogy Mapping Orbiter, a 12U CubeSat to be launched in 2023 with the goal of understanding the composition and distribution of water ice near the lunar South pole. Spacecraft configurations based on chemical and electric propulsion systems are investigated and compared for different candidate science orbits and rideshare opportunities.

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AAS 21-252

ESCAPE TRAJECTORIES FROM LAGRANGIAN POINTS WITH ELECTRIC PROPULSION

Luigi Mascolo[*] and Lorenzo Casalino[†]

An indirect method to determine optimal low-thrust trajectories for the escape from Earth's sphere of influence starting from Sun-Earth or Earth-Moon L2 is developed. The highly chaotic and non-linear dynamics of motion close to Lagrangian points challenges the remarkable precision of the indirect method: different approaches and improvements, such as multifield and possibly multipleshooting methods, are identified and implemented to handle these numerical problems. The dynamic model considers 4-body gravitation, JPL ephemeris, and may include spherical harmonic models for Earth and Moon; solar radiation pressure is also considered. Results show single burn escape trajectories from Sun-Earth L2 and the relatively small influence of perturbations on C3 and propellant requirements. Single-burn and two-burn trajectories are required for escape from Earth-Moon L2, with large influence on performance by the relative positions of Sun and Moon.

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AAS 21-257

A FUNCTIONAL INTERPOLATION APPROACH TO COMPUTE PERIODIC ORBITS IN THE CIRCULAR RESTRICTED THREE-BODY PROBLEM[*]

Hunter Johnston,[†] Martin W. Lo,[‡] and Daniele Mortari[§]

In this paper, we develop a method to solve for periodic orbits, i.e., Lyapunov and Halo orbits, using a functional interpolation scheme called the Theory of Functional Connections (TFC). Using this technique, a periodic constraint is analytically embedded into the TFC constrained expression. By doing this, the system of differential equations governing the three-body problem is transformed into an unconstrained optimization problem where simple numerical schemes can be used to find a solution, e.g., nonlinear least-squares is used. This allows for a simpler numerical implementation with comparable accuracy and speed to the traditional differential corrector method.

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AAS 21-274

ANALYTICAL PARTIAL DERIVATIVES OF THE Q-LAW GUIDANCE ALGORITHM

Jackson L. Shannon,[*] Donald Ellison,[†] and Christine M. Hartzell[‡]

The closed-loop Q-Law guidance algorithm has been shown to be a very capable and efficient method for producing low-thrust trajectories. This paper poses a Q-Law optimization problem for computing locally optimal gain values using nonlinear programming (NLP) and for enforcing nonlinear constraints on the initial state. Gradient-based optimization methods have been shown to benefit greatly when analytical partial derivatives are supplied to the optimizer, therefore, we present derivations of the Q-Law thrust vector partial derivatives with respect to the Q-law gains as well as with respect to the spacecraft's state. These partials are leveraged to produce a state transition matrix, which contains exact partial derivatives of the terminal state with respect to the NLP decision vector.

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COMBINED B-PLANE AND PICARD-CHEBYSHEV APPROACH FOR THE CONTINUOUS DESIGN OF PERTURBED INTERPLANETARY RESONANT TRAJECTORIES

Alessandro Masat,* Matteo Romano† and Camilla Colombo‡

Orbital resonances have been exploited in different contexts, with the latest interplanetary application being the ESA/NASA mission Solar Orbiter, which uses repeated flybys of Venus to change the ecliptic inclination with low fuel consumption. The b-plane formalism is a clever framework to represent close approaches at the boundaries of the sphere of influence of the flyby planet. This representation is exploited to prune the design of perturbed resonant interplanetary trajectories in reverse cascade, without patched conics approximation. The design strategy is formulated as a multi-layer optimization problem, whose core numerically integrates the perturbed orbital motion with the Picard-Chebyshev integration method. The analytical pruning solution is also used as starting guess to ensure the fast convergence of both the numerical integration and the design algorithm. The proposed semi-analytical strategy allows to surf complex gravitational perturbing effects optimizing artificial maneuvers in a computationally efficient way, and can be extended to account for any other perturbation source. The method is applied to the design of a Solar Orbiter-like quasi-ballistic first resonant phase with Venus.

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AAS 21-291

MULTIDISCIPLINARY SYSTEM DESIGN OPTIMIZATION OF LUNAR SURFACE ACCESS FROM CISLUNAR ORBIT VIA SURROGATE-ASSISTED EVOLUTIONARY ALGORITHMS USING HIGHLY-PARALLEL GPU ARCHITECTURE

Kyuto Furutachi,* Hideaki Ogawa,† and Satoshi Ueda‡

Global optimization draws increasing attention with the advancement of space missions and the increasing complexity of spacecraft systems. This paper aims to demonstrate a multidisciplinary system design optimization (MSDO) framework using a surrogate-assisted evolutionary algorithm with the aid of highly-parallel GPU architecture being performed. Lunar surface access mission from cislunar orbit is adopted to demonstrate this framework, which consists of the following phases; (1) transfer to a low lunar orbit (LLO); and (2) landing on the lunar surface from LLO. The objective of MSDO is to minimize the time of flight and the ratio of payload mass with respect to the spacecraft payload subject to two constraints. As a result of MSDO, a Pareto optimal front has been obtained, and a series of nondominated solutions have been identified. The proposed framework and the resultant solution of multidisciplinary system design optimization have been examined by means of statistical methods including global sensitivity analysis and scatter plot matrix.

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AAS 21-292

EQUULEUS LAUNCH WINDOW ANALYSIS AND MISSION DESIGN

**Diogene A. Dei Tos,[*] Takuya Chikazawa,[†] Yosuke Kawabata,[‡]
Kota Kakihara,[§] Nicola Baresi,[**] Stefano Campagnola,[††]
and Yasuhiro Kawakatsu[‡‡]**

This paper presents the trajectory design process for EQUULEUS, a 6U CubeSat developed by JAXA and the University of Tokyo that is scheduled to launch as a piggyback of NASA's Artemis 1. After separation from the upper stage of the Space Launch System, EQUULEUS will maneuver along a low-energy transfer to an Earth–Moon quasi-rectilinear halo orbit in 1-to-4 resonance with the lunar synodic period. As a secondary payload, the trajectory of EQUULEUS needs to be compatible with the requirements of the primary mission, but also robust against disturbances and potential changes in the deployment state. Realistic initial conditions spanning two years of potential launch windows are processed and the solution structure for optimal lunar transfers is analyzed. A host of candidate solutions is presented, compatibly with the fuel and power limitations of EQUULEUS. The global understanding of the solution space is shown to be insightful for the design of robust trajectories for limited control-authority spacecraft.

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AAS 21-320

GLOBAL TRAJECTORY OPTIMIZATION OF EARTH-NRHO TRANSFER USING WEAK STABILITY BOUNDARY VIA GPU-BASED SUPER-PARALLELIZATION

Satoshi Ueda[*] and Hideaki Ogawa[†]

This paper presents a global trajectory optimization framework via a multi-fidelity approach that utilizes a GPU for low-fidelity initial solution search and a CPU to determine high-fidelity feasible solutions. A multi-fidelity approach is proposed to enable global trajectory optimization of Earth-NRHO transfer. The present study employs a weak stability boundary transfer that utilizes solar tidal force for velocity increment saving. The resultant trajectories are examined in a Pareto optimal front with respect to two objectives (*i.e.*, velocity increment and flight time) in prospect of application to realistic missions. Surrogate models that represent the relations between the decision variables and performance parameters (*i.e.*, velocity increments) are constructed from the perspective to be employed in the framework for MSDO problems. Variance-based global sensitivity analysis is performed to assess each decision variable's impact on the performance parameters. The results and insights are summarized for the resultant global structure of feasible solutions, while verifying the capability and effectiveness of the global design framework enabled by a GPU-based highly parallel architecture.

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AAS 21-334

I'LL HAVE THE PORTER: INTERACTIVELY VISUALIZING THE RESULTS OF STATISTICAL MANEUVER ANALYSIS

Rohan Patel,[*] Jimmy Moore,[†] Jeffrey Stuart,[‡] Sonia Hernandez,[‡] and Basak Alper Ramaswamy[§]

Mission design and navigation relies on statistical maneuver analysis and Monte Carlo simulations when evaluating candidate mission trajectories. Engineers must analyze large quantities of data to optimize mission safety and propellant margins, but currently rely on static text files and dense PDF slide decks to review simulation results. This approach is time-intensive, non-interactive, and difficult to share or coordinate with other mission designers. To improve this process, we present Porter: a web-based interactive mission analysis tool. This work describes Porter's user-centered design process, its processing pipeline for importing and processing LAMBIC simulation data, core interactive features, and preliminary user feedback.

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AAS 21-345

RECOVERY TRAJECTORIES FOR INADVERTENT DEPARTURES FROM AN NRHO

Emily M. Zimovan-Spreen,[*] Diane C. Davis,[†] and Kathleen C. Howell[‡]

The current Gateway baseline orbit, a Near Rectilinear Halo Orbit (NRHO), is a nearly stable orbit that requires regular orbit maintenance (OM) maneuvers for long-term retention of a spacecraft. With missed OM maneuvers, particularly over extended intervals, spacecraft naturally depart from the baseline orbit. In response, a strategy to recover inadvertent departure trajectories and return a spacecraft to the NRHO is developed. A Monte Carlo-based approach is used to analyze departures that are recoverable using a standard OM approach. Dynamical structures in the vicinity of the NRHO are leveraged to design recovery trajectories for spacecraft that have departed further from the baseline.

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AAS 21-372

STUDY ON INTERPLANETARY TRAJECTORIES TOWARDS URANUS AND NEPTUNE

Francesco Sena,* Andrea D'Ambrosio,† and Fabio Curti‡

To better understand the origin and evolution of our Solar System, the Ice Giants could represent a coveted destination in future decades. In this work, possible interplanetary trajectories towards Uranus and Neptune have been investigated in the 2025-2100 timeframe to provide a preliminary idea of fuel consumption in terms of Δv related to different mission durations and to pinpoint convenient launch opportunities during the century. The study is developed using the ESA's Advanced Concept Team open-source libraries PyKEP and PyGMO, analyzing and comparing two different Multiple Gravity-Assist (MGA) trajectory schemes. The first one involves a Deep-Space Maneuver per leg (MGA-1DSM) and the other one exploits just a Flyby Pericenter Maneuver (Powered-MGA or PMGA). The research considers only trajectories with Gas Giants gravity-assist maneuvers. The results show, for the same time of flight, more expensive trajectories in terms of Δv for the MGA-1DSM with respect to PMGA. Therefore, the latters are further analyzed varying the time of flight. Feasible trajectories and launch opportunities towards Uranus and Neptune are obtained with a total Δv of about 2 km/s and 3 km/s, respectively. Finally, close launch opportunities for both Uranus and Neptune are respectively investigated in 2035 and in 2033.

[View Full Paper]

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AAS 21-377

PRELIMINARY MISSION DESIGN FOR PROPOSED NUSOL PROBE

Kyle Messick,[*] Atri Dutta,[†] Holger Meyer,[‡] Mark Christl,[§] and Nick Solomey[**]

A solar neutrino detector has never flown in space. NuSol is a proposed mission to fly a solar neutrino detector close to the Sun in order to conduct unique science objectives that cannot be realized by detectors on Earth. The paper presents a preliminary trajectory design for the NuSol mission in order to accomplish the science goals, taking into account specified mission cost constraints, a given launch window, and an overall mission duration. Numerical simulations are presented to compare different mission scenarios and to identify a trajectory design that realizes the science goals of the mission.

[View Full Paper]

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AAS 21-392

EFFECT OF V-INFINITY LEVERAGING WITH LUNAR-EARTH GRAVITY ASSIST ON INTERPLANETARY TRAJECTORIES

Giuliana Elena Miceli*

This work evaluates the effects of Lunar-Earth Gravity Assist on mission design and ΔV budget for interplanetary trajectories using Earth flybys and V∞ Leveraging Maneuvers. The use of the Moon flyby, in combination to the Earth flyby, provides additional deviation of the hyperbolic excess velocity with respect to the Earth, also modifying its magnitude, and hence increases the overall flyby performance. The Lunar-Earth Gravity Assist has been evaluated for Exterior and Interior Leveraging, as well as for Short and Long transfers. A sample Jupiter mission is showcased for six resonant orbits. The results suggest that the application of a Lunar-Earth Gravity Assist on the most fuel efficient transfer ((E)2 : $1^{-}{}_{1}$ orbit) reduces the ΔV_{tot} by 5.3%, compared to the same results obtained with the Earth Gravity Assist. The maximum reduction is obtained with (E)3 : $2^{+}{}_{1}$ orbit, where the ΔV_{tot} is lowered by 6.4% and the $\Delta V_{V\ ILM}$ by 21.06%.

[View Full Paper]

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AAS 21-399

ACCELERATION-BASED INDIRECT METHOD FOR CONTINUOUS AND IMPULSIVE TRAJECTORY DESIGN

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

A novel acceleration-based formulation is proposed to construct minimum-ΔV bang-off-bang thrust profiles and impulsive maneuvers in a rapid manner. The proposed methodology leads to substantial simplifications by removing mass state, thrust magnitude and specific impulse values from the ensuing boundary-value problems. Standard acceleration-based methods form a quadratic cost to avoid singular arcs and to solve the resulting optimal control problems. We propose a method based on a linear acceleration term that achieves the desired bang-off-bang control structure by enforcing a maximum acceleration parameter. Impulsive trajectories are obtained for large values of the acceleration parameter. Utility of the method is demonstrated for transfer maneuvers between orbits in two-body dynamics and in the Earth-Moon circular restricted three-body dynamical model.

[View Full Paper]

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AAS 21-403

PERIAPSIS TARGETING WITH WEAK STABILITY BOUNDARY TRANSFERS FOR ORBITING AROUND PLANETARY MOONS

Yuri Shimane*

This work proposes an alternative approach for periapsis targeting with weak stability boundary transfers (WSBT). This is conducted in the circular restricted three body problem (CR3BP) to generate preliminary solutions for subsequent trajectory refinement in higher-fidelity models. Specifically, a design procedure for targeting the periapsis of a celestial body with a WSBT is proposed based on a grid-based manifold sampling technique. Compared to conventional hyperbolic approaches, WSBT offers a significant reduction in delta-V required for insertion into a destination orbit, thus providing an attractive alternative approach for mission designers.

[View Full Paper]

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AAS 21-405

ROBUST MULTI-BODY SLEWING TRAJECTORIES VIA UNSCENTED OPTIMAL CONTROL

Brian W. Bishop,* Richard G. Cobb,† and Costantinos Zagaris‡

Traditional trajectory generation for multi-body reorientation maneuvers rely upon simplified kinematic principles employing conservative constraints on maximum gimbal torque and velocity to minimize disturbances. Techniques such as notch filtering or input shaping are standard tools to increase robustness and reduce excitation of structural modes. This manuscript investigates the use of unscented optimal control techniques to generate maneuvers robust against uncertain parameters while simultaneously decreasing maneuver length and minimizing system vibrational excitation. The proposed method employs pseudospectral optimal control while leveraging the unscented transform to cast stochastic parametric uncertainty into a deterministic problem formulation. The performance and robustness of the resulting trajectories are compared against standard maneuvers, demonstrating superior performance of the proposed method.

[View Full Paper]

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AAS 21-426

INTERPLANETARY TRAJECTORY DESIGN FOR A HYBRID PHOTONIC-ELECTRIC PROPULSION SYSTEM DEPARTING FROM CISLUNAR ORBITS

Yuki Takao* and Toshihiro Chujo†

A hybrid system consisting of solar photonic-electric propulsion for use in deep space exploration is investigated. The simultaneous use of photonic and electric propulsion, which is accomplished by a solar sail equipped with thin-film solar cells, enhances the thrust performance of a space probe. Making use of each propulsion system depending on the sun distance can cover a wide area in deep space, which in turn extends the possible regions to be explored. In this study, assuming interplanetary missions departing from an exploration base on cislunar orbits, a trajectory design method for the hybrid propulsion system is presented.

[View Full Paper]

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AAS 21-452

LUNAR IMPACT PROBABILITY FOR SPACECRAFT IN NEAR RECTILINEAR HALO ORBITS

Diane C. Davis,[*] Rolfe J. Power,[†] Kathleen C. Howell,[‡] and Jeffrey P. Gutkowski[§]

Near Rectilinear Halo Orbits (NRHOs) near the Moon are of recent interest for missions including Gateway and CAPSTONE. To address planetary protection considerations during long-term NRHO operations, the probability of impact on the lunar surface following a wide range of Δv perturbations is assessed. The effects of the distribution of disturbances occurring at various locations around the NRHO and the short-term destination of the escaping particles are explored. The likelihoods of collision across the entire lunar surface and within sensitive polar regions are considered in both the circular restricted 3-body model and in the higher-fidelity ephemeris force model.

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SPACECRAFT CONTROL

Session Chairs:

Session 13: Francesco Topputo, Politecnico di Milano

Session 17: Ossama Abdelkhalik, Iowa State University

The following papers were not available for publication:

AAS 21-412 Paper Withdrawn

AAS 21-418 Paper Withdrawn

AAS 21-210

MODIFYING AND OPTIMIZING THE INVERSE OF THE FREQUENCY RESPONSE CIRCULANT MATRIX AS AN ITERATIVE LEARNING CONTROL COMPENSATOR

Shuo Liu* and Richard W. Longman†

Feedback control systems do not do what you ask. The concept of bandwidth is defined to tell what components of a command are reasonably well handled. Iterative Learning Control (ILC) seeks to converge to zero error following any given finite time desired trajectory as iterations progress. The approach can be used to achieve high precision tracking in spacecraft sensors performing repeated highly accurate sensor scanning. ILC asks for zero error for a finite time tracking maneuver, containing initial transients each iteration. The purpose of this paper is to create a method of designing ILC compensators based on steady state frequency response, and have the ILC converge to zero error in spite of transients and bandwidth. In this work the inverse of the circulant matrix of Markov parameters is used as a learning gain matrix. One can show that this matrix gives the steady state frequency response of the system at the finite number of frequencies observable in the finite data sequence of an iteration or run. Methods are used to adjust the steady state frequency response gains to address the transient part of the error signal. Numerical simulations compare the design approach to common time domain ILC design approaches, and one observes much faster convergence.

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AAS 21-239

ITERATIVE LEARNING CONTROL INVERSE PROBLEM USING HARMONIC FREQUENCY FILTERS

Jer-Nan Juang* and Richard W. Longman†

Basic learning control law designs are summarized, and conditions for convergence of the learning process are developed when several different choices of filter frequency cut-offs are used for robustification. This paper presents a cliff harmonic-frequency filter with a sharp frequency cutoff and a weighted harmonic-frequency filter with frequency weighting, that are applied each iteration in iterative learning control. Filter matrices based on the state-space model of a finite-difference digital filter are derived for Matlab's and Gustafsson's forward and backward filtering which are commonly called filtfilt methods. Furthermore, filter matrices for Matlab's and Gustafsson's filtfilts are revised to make the input convergence matrix to be monotonically stable. Numerical examples are used to demonstrate the effectiveness of the harmonic-frequency filters comparing with Matlab's and Gustafsson's filtfilt methods based on Butterworth filters of different orders and cutoff frequencies. It is found that the singular values of filter matrices are related to the squared amplitude of the Butterworth filter at harmonic frequencies.

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AAS 21-247

STUDY ON AUTONOMOUS GRAVITY-ASSISTS WITH A PATH FOLLOWING CONTROL

Rodolfo B. Negri[*] and Antônio F. B. de A. Prado[†]

An autonomous control of gravity-assist hyperbolic trajectories is studied. In order to do so, it is applied a path following control law that uses sliding mode control theory to guarantee robustness to bounded disturbances. Monte Carlo simulations in Titan and Enceladus, considering high insertion errors in the order of 50 km, prove the effectiveness of the proposed strategy. In particular, the Enceladus example, in which the control has to stabilize the orbital geometry in a short time span avoiding a collision, and making a close-approach 10 km above Enceladus' surface, indicates that the control has special applicability for asteroids and small moons close flybys for science observations. Applying the control in the context of a Jovian tour, considering a N-body problem, with the nominal trajectory calculated by patched conics, indicates that a flyby control by itself is not able to guarantee a tour. In this case, the vehicle guidance should be more precise than a patched conics model.

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AAS 21-255

A NEAR-OPTIMAL ATTITUDE CONTROL FOR AN EARTH IMAGING SATELLITE

Giovanni Lavezzi* and Marco Ciarcià†

In this work, we describe a near-optimal attitude control strategy for an Earth imaging satellite. The maneuver scenario includes an initial target acquisition phase followed by a slewing phase, to maintain a high accuracy pointing of the same area. The proposed strategy is based on a direct method, the Inverse Dynamics in the Virtual Domain, for the transcription of the original optimal control problem into an equivalent nonlinear programming problem. A nonlinear programming solver, the Sequential Gradient-Restoration Algorithm, is then used for the fast calculation of the solution trajectory. The attitude guidance is achieved by implementing the rapid generation of the near-optimal control torques in a closed-loop fashion. Both minimum time and minimum control energy criteria are considered. We compare the proposed methodology against conventional attitude controllers, a quaternion feedback Proportional-Derivative controller and a Linear Quadratic Regulator. Optimality and accuracy of these methodologies are assessed for several target acquisitions. The tracking maneuvers are performed in a high-fidelity simulation environment which includes disturbance torques and a model of the actuation device.

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AAS 21-262

ADAPTIVE CONTROL FOR PROXIMITY MANEUVERS AROUND ASTEROIDS USING EXTREME LEARNING MACHINE-BASED GRAVITY FIELD ESTIMATION

Andrea D'Ambrosio,[*] Gabriele Conforti,[†] Ivan Agostinelli,[‡] and Fabio Curti[§]

Proximity operations around asteroids are challenging because of the difficulties in the real-time estimation of their gravity field. Additionally, it is extremely important to design control strategies to perform essential maneuvers. In this paper, direct adaptive control is employed to study proximity maneuvers around asteroids, such as hovering and orbit station keeping. Thanks to this approach, the control law is directly adjusted to minimize the error between plant and reference trajectory outputs. The control law's gains are tuned to obtain the desired performances. Furthermore, to consider a fast and accurate estimation of the gravity, Extreme Learning Machine is exploited to map the position vector into the gravity vector in the asteroid body-fixed frame. Finally, all the framework is applied to proximity maneuvers around asteroid 951 Gaspra, obtaining good results.

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AAS 21-263

REDUCED CONTROL AUTHORITY IN A DISPERSED SATELLITE FORMATION ANTENNA ARRAY

Mason Nixon* **and Yuri Shtessel†**

Key technologies in small satellites, spacecraft control, and antenna arrays have come about in recent years. Previously, we described new control techniques for a novel satellite formation architecture wherein each satellite acts as an independent antenna in a satellite formation. This has the potential to facilitate increased data transmission performance, reconfigurability, adaptive beamforming, robustness to noise and interference, increased gain, and other benefits. For small satellites, propulsion and/or actuation can be limited within each dimension or axis, leading to reduced control authority. We address the control problem for this type of system with perturbations using adaptive sliding mode control techniques.

[View Full Paper]

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AAS 21-272

IDENTIFICATION OF THE DYNAMICS IN THE SINGULAR VECTORS OF THE SYSTEM TOEPLITZ MATRIX OF MARKOV PARAMETERS

Jer-Nan Juang* **and Richard W. Longman†**

Singular value decomposition of the system Toeplitz matrix of Markov parameters plays a major role in designing an iterative learning controller. It is found that each left or right singular vector can be considered as a free response of a linear model. A linear system identification method is used to identify the modal parameters such as frequencies and damping ratios. Each singular vector decomposed from a Toeplitz matrix contains at least a pure frequency. Numerical examples for several different system orders are used to show the characteristics of identified eigenvalues embedded in the singular vectors.

[View Full Paper]

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AAS 21-278

DESIGN TRADEOFFS USING SECOND ORDER REPETITIVE CONTROL TO REDUCE SENSITIVITY TO DISTURBANCE PERIOD

Ayman F. Ismail[*] and Richard W. Longman[†]

Repetitive control (RC) is a widely used effective approach for tracking periodic references and rejecting period disturbances to a feedback control system. Spacecraft often have vibrations from slight imbalances in the moving parts of a cryogenic pump, CMG's, or reaction wheels. RC is one candidate for producing active vibration isolation of such fine pointing equipment. Two different RC challenges can be encountered in applications that cause the period of the disturbance to vary. Either the disturbance period is not known to high precision or the known period is subject to fluctuations from random unmodeled effects. In some cases, the variations in disturbance period are relatively slow and allow for adjustments to be made. In other cases, the period fluctuates fast and requires the RC design to be robust enough to handle such fluctuations. Higher order RC (HORC) including second order RC (SORC) has previously been introduced to improve the robustness to period variations by incorporating a negative weight(s) on errors from previous period(s). This paper investigates different SORC designs for the purpose of improving robustness to period uncertainties. It also emphasizes the tradeoffs that must be made during the design phase, including competing factors such as the needed notch width for allowable variations in disturbance period with respect to the fundamental frequency and the distortion characteristics at the harmonics, etc. The methodology is demonstrated through tradeoff curves for various controller design parameters and levels of variation in disturbance period. To further improve the robustness of SORC, a high frequency zero-phase low-pass filter is proposed to cutoff the RC action above a certain harmonic based on inaccuracy in knowledge of the period.

[View Full Paper]

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AAS 21-279

CONTROLLER DESIGN FOR LAUNCH VEHICLE WITH INTERNAL TORQUE

Ryan Kinzie* and Dongeun Seo†

A linear quadratic regulator and PD-type controller are proposed to stabilize a launch vehicle with an internal torque and unknown internal engine dynamics. This research uses a nonlinear six degree-of-freedom rigid body model of a theoretical launch vehicle to compare the linear time-invariant linear quadratic regulator with the linear time-invariant PD-type controller. The novelty of this study is that no previous studies have investigated the control of a launch vehicle which has an internal toque nor unknown internal engine dynamics. This research shows that a linear time-invariant PD-type controller provides adequate control over the theoretical launch vehicle with an engine originating internal toque and unknown internal engine dynamics. The performance of the proposed controller is demonstrated by numerical simulations.

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AAS 21-294

ROBUST ADAPTIVE CONTROL FOR ATTITUDE CONTROL OF SPACECRAFT FORMATION FLYING

Soobin Jeon,[*] Hancheol Cho,[†] and Sang-Young Park[‡]

This paper develops continuous adaptive controllers for precision attitude control of spacecraft formation flying in the presence of the unknown, but bounded external disturbances and uncertainties in the dynamic model. Based on the concept of sliding mode control theory, a continuous control law that is linear in the sliding variable is designed to avoid chattering and to guarantee finite-time convergence of the sliding variable to a user-specified small domain for nonzero initial errors. In addition, a simple gain adaptation law is proposed that automatically updates the control gain without a priori knowledge of the uncertainties associated with the attitude dynamics. Numerical simulations are carried out to demonstrate the robustness and accuracy of the proposed adaptive control strategy, where the orientation of a spacecraft in the CANYVAL-C mission is required to track a time-varying thrust vector and shade the Sun by the occulter, while compensating for the effects of external disturbances and uncertainties in the moment of inertia values.

[View Full Paper]

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AAS 21-319

PHYSICS INFORMED NEURAL NETWORKS FOR HAMILTON JACOBI BELLMAN EQUATIONS FOR A CLASS OF OPTIMAL CONTROL PROBLEMS

Roberto Furfaro,* Andrea Scorsoglio,† and Enrico Schiassi‡

In this paper, finite and infinite horizon optimal control problems with quadratic cost are solved via a dynamic programming approach using Physics-Informed Neural Networks (PINNs). In particular, the arising Hamilton Jacobi Bellman partial differential equation, that guarantees a necessary and sufficient condition for the optimality and provides a closed loop solution, is solved via PINNs. PINNs are particular neural networks where the training is regulated by the physics of the problem, modeled through differential equations. Here, two different PINN frameworks are considered: the standard PINN, and the Deep Theory of Functional Connections (Deep-TFC). The main difference between these two PINN frameworks is that with Deep-TFC initial and boundary conditions are analytically satisfied using the Constrained Expressions (CEs), introduced with the original Theory of Functional Connections (TFC). These expressions are a sum of a free-function and a functional that analytically satisfies the boundary constraints regardless to the choice of the free-function. According to the Deep-TFC method, the free-function is a deep neural network trained via gradient based method. The results show the convenience in employing PINN frameworks, as they are relatively easy to implement and can overcome the issue of the curse of dimensionality.

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CLOSED-LOOP OPTIMAL CONTROL FOR SPACECRAFT RENDEZVOUS AND PROXIMITY OPERATIONS USING SECOND-ORDER CONE PROGRAMMING

Michael D. Devore,[*] Richard J. Adams,[†] Adam Reed,[‡] Alexander Lewis,[§] and Ping Lu[**]

Solutions to autonomous guidance and control problems for spacecraft rendezvous and proximity operations (RPO) must handle complex multiple phase missions while being robust to modeling uncertainties, unmodeled dynamics, and external disturbances. This paper presents a closed-loop control approach based on second-order cone programming (SOCP) that supports continuous regeneration of a fuel-optimal control solution that satisfies inequality constraints as well as equality constraints on interior points and terminal conditions within a multi-phase mission. Through a lossless relaxation technique and a novel successive solution approach, a nonlinear RPO problem is transformed into sequence of sub-problems that are solved by a primal-dual interior-point method. By periodically exercising this process over the course of a mission using continuously-evolving state estimates, the technique takes the form of a closed loop optimal control solution. The approach is demonstrated in high-fidelity nonlinear simulations including an autonomous rendezvous, proximity operations, and docking (ARPOD) mission with an ellipsoidal keep-out region and a forced circumnavigation (FCN) mission.

[View Full Paper]

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AAS 21-390

LYAPUNOV-BASED CONTROL OF KINEMATICALLY COUPLED CLOSE-PROXIMITY SPACECRAFT FEATURE POINT DYNAMICS

Eric A. Butcher* and Chad Wenn†

A nonlinear Lyapunov-based strategy for the 6-DOF control of kinematically coupled close-proximity spacecraft feature point dynamics is presented in which the feature points on the chief and deputy spacecraft are not the centers of gravity but some points of interest such as a docking port. The relative dynamics of the CGs are described by the HCW equations or alternative equations of relative motion, while additional terms account for the kinematic orbit/attitude coupling. The Mukherjee-Chen theorem is used to guarantee asymptotic stability. To eliminate the attitude tracking error, three different quaternion-based Lyapunov functions with corresponding feedback controls are compared.

[View Full Paper]

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AAS 21-391

MODELING AND CONTROL OF AN ELECTROMAGNETIC DOCKING SYSTEM FOR THE SAS-SAT CUBESAT MISSION

Kyle Rankin,[*] Hyeongjun Park,[†] and Steven Stochaj[‡]

The Satellite Alignment System SATellite (SAS-SAT) demonstrates a low-cost system to perform the final approach to docking between two CubeSats utilizing electromagnets as actuators. This paper shows the development of the dynamics model and goes into a detailed analysis of the control system design, including both a PID, and a Bang-Bang controller. This paper presents the validation used for the system model and the preliminary design of the SAS-SAT docking system.

[View Full Paper]

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CISLUNAR SPACE SITUATIONAL AWARENESS

Session Chair:

Session 14: Brandon Jones, The University of Texas at Austin

The following paper was not available for publication:

AAS 21-225 Paper Withdrawn

CISLUNAR SPACE SITUATIONAL AWARENESS

Carolin Frueh,[*] Kathleen Howell,[†] Kyle J. DeMars,[‡] and Surabhi Bhadauria[§]

Classically, space situational awareness (SSA) and space traffic management (STM) focus on the near-Earth region, which is highly populated by satellites and space debris objects. With the expansion of space activities further in the cislunar space, the problems of SSA and STM arise anew in regions far away from the near-Earth realm. This paper investigates the conditions for successful Space Situational Awareness and Space Traffic Management in the cislunar region by drawing a direct comparison to the known challenges and solutions in the near-Earth realm, highlighting similarities and differences and their implications on Space Traffic Management engineering solutions.

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AAS 21-406

OBSERVABILITY METRICS FOR SPACE-BASED CISLUNAR DOMAIN AWARENESS

Erin E. Fowler,[*] Stella B. Hurtt,[†] and Derek A. Paley[‡]

We present a dynamic simulation of the cislunar environment for use in numerical analysis of various pairings of resident space objects and sensing satellites intended for cislunar space domain awareness (SDA). This paper's contributions include analysis of orbit families for the mission of space-based cislunar domain awareness and a set of metrics that can be used to inform the specific orbit parameterization for cislunar SDA constellation design. Additionally, by calculating the local estimation condition number, we apply numerical observability analysis techniques to observations of satellites on trajectories in the Earth-Moon system, which has no general closed-form solution.

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AAS 21-450

GROUND-BASED NAVIGATION TRADES FOR OPERATIONS IN GATEWAY'S NEAR RECTILINEAR HALO ORBIT

Matthew Bolliger,[*] Michael R. Thompson,[*]
Nathan P. Ré,[†] Connor Ott,[*] and Diane C. Davis[‡]

This paper presents an analysis of ground-based tracking during operations in a 9:2 synodic-resonant Earth-Moon L_2 southern NRHO. The purpose of this work is to inform Gateway requirements and operations planning. The performance of different tracking configurations is compared in terms of the annual orbit maintenance ΔV, state uncertainties, state errors, and filter reliability. Tracking configurations are parameterized based on track durations, locations within the NRHO, and number of tracks per revolution. Filter configurations are parameterized in terms of stochastic acceleration, *a priori* uncertainty passed from orbit-to-orbit, estimated parameters, and considered parameters. Monte Carlo analysis with simulated observations is performed on each of 44 tracking configurations and 16 filter configurations. The resulting filter solutions are compared to a notional reference requirement of 10 km, 10 cm/s state uncertainty.

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DYNAMICAL SYSTEM THEORY

Session Chairs:

Session 15: Donghoon Kim, University of Cincinnati

Session 28: Amanda Haapala, Johns Hopkins University Applied Physics Laboratory

AAS 21-212

GLOBAL L2 QUASI-HALO FAMILY AND THEIR CHARACTERISTICS

David Lujan* and Daniel J. Scheeres†

A preexisting algorithm for computing quasi-periodic orbits called GMOS is used to explore the boundaries of the L2 quasi-halo family in the Earth-Moon system. An algorithm is developed to explore the family utilizing one-dimensional straight line continuation in frequency space. This work provides insight into the family's boundaries and characteristics, including their frequencies, Jacobi energies, perilunes, and apolunes. The effects of resonances between the frequencies of quasi-periodic orbits is clearly observed, highlighting their importance when computing this class of orbits. A method for obtaining principle family tangent vectors and continuing families of quasi-periodic orbits along lines of constant slopes in frequency space is presented.

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AAS 21-222

A RAPID METHOD FOR ORBITAL COVERAGE STATISTICS WITH J_2 USING ERGODIC THEORY

Andrew J. Graven,* Alan H. Barr,† and Martin W. Lo‡

Quantifying long-term statistical properties of satellite trajectories typically entails time-consuming trajectory propagation. We present a fast, ergodic[1] method of analytically estimating these for J_2 perturbed elliptical orbits, broadly agreeing with trajectory propagation-derived results. We extend the approach in Graven and Lo (2019)[2] to estimate: (1) Satellite-ground station coverage with limited satellite field of view and ground station elevation angle with numerically optimized formulae, and (2) long-term averages of general functions of satellite position. This method is fast enough to facilitate real-time, interactive tools for satellite constellation and network design, with an approximate 1000× GPU speedup.

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AAS 21-244

LOW-ENERGY TRANSFERS BETWEEN PLANAR AND SPATIAL PERIODIC ORBITS VIA VERTICAL INSTABILITY AROUND EARTH-MOON L_1

Kenta Oshima*

This paper presents a method of designing low-energy transfers changing the out-of-plane amplitude substantially around a libration point L1 via the vertical instability of planar Lyapunov orbits in the Earth-Moon circular restricted three-body problem. A sequence of optimizations onto short-term stable manifolds associated with the weak vertical instability emanating from planar Lyapunov orbits generates multi-revolutional, low-energy trajectories reaching substantial out-of-plane amplitudes against the stronger horizontal instability. As applications, the trajectories are used to compute transfers between planar Lyapunov orbits and three-dimensional vertical Lyapunov and halo orbits with wide ranges of time-of-flight and delta-v.

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AAS 21-250

HAND-ARM COORDINATION CONTROL FOR TUMBLING TARGET CAPTURE USING STABLE ESTIMATOR OF DYNAMICAL SYSTEMS

Liping Fang,[*] Quan Hu,[†] Fei Liu,[‡] Yueyang Hou,[§,**] Shan Lu,[§,**]

In this work, the Stable Estimator of Dynamical Systems (SEDS) is applied to the free-floating space robot system for tumbling target capture. Learning from successful capture demonstrations for a tumbling target, two dynamical systems are established. One is for the trajectory generation of the manipulator, and the other is for the motion control of the end effector. Then they are coupled together to precisely control the motion of the end effector. In addition, a data-driven probabilistic approach is used to establish the reachable space model of the manipulator and the graspable model of the target, respectively. The optimal capture configuration is determined by finding the configuration with the highest probability. Finally, the effectiveness of the approach is evaluated through numerical simulations.

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AAS 21-256

QUASI-PERIODIC ORBIT TRANSFERS VIA INTERSECTING TORUS WHISKERS

Damennick B. Henry* and Daniel J. Scheeres†

The ability to transfer between orbits is a necessary component of many space missions. Transfers between the most abundant type of orbit, quasi-periodic orbits (QPOs), remain largely unstudied. This paper presents a methodology for transferring between hyperbolic QPOs by computing position intersections between their invariant manifolds. Fundamental to the methodology is the treatment of QPOs as quasi-periodic tori and the manifolds as the associated whiskers. The approach is general and can be applied to a wide variety of dynamical systems. Numerical examples are given in the circular restricted three body problem model of the Earth-Moon system.

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AAS 21-265

CUBESAT LUNAR TRANSFER DESIGN VIA WEAK STABILITY BOUNDARIES

Danny Owen,[*] Xiaoyu Fu,[†] and Nicola Baresi[‡]

CubeSat missions that take advantage of ride-sharing opportunities to the Moon are typically limited by a small Δv budget. In this paper, a patching point method is applied to design a low-energy lunar transfer for a spacecraft initially placed into a circumlunar free-return trajectory. Initial conditions generated within weak stability boundaries further guarantee ballistic lunar capture upon arrival. A large number of optimised trajectories are produced, with a minimum mission Δv cost of 32.51 m/s. Additionally, the B-plane values of the spacecraft during its initial flyby of the Moon are investigated. A relationship between the initial position of the Sun in the synodic frame and the B-plane values is observed, in which successful trajectories appear to favour entering into certain orbital resonances with the Moon.

[View Full Paper]

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AAS 21-270

QUASI-PERIODIC ORBITS IN THE SUN-EARTH-MOON BICIRCULAR RESTRICTED FOUR-BODY PROBLEM

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

Examining the properties of quasi-periodic orbits provides insight into the Sun-perturbed environment in cislunar space. In this investigation, quasi-periodic trajectories and their properties are explored in a Sun-Earth-Moon Bicircular Restricted Four-Body Problem (BCR4BP). Additionally, computation and stability of invariant torus families in the BCR4BP are detailed. Understanding quasi-periodic behavior in the BCR4BP expands available options for path planning to destinations in the lunar vicinity.

[View Full Paper]

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AAS 21-307

DESIGN OF SOLAR SAILING IN SUN-EARTH-MOON SYSTEM AND TRANSFER TO INTERPLANETARY REGION

Toshihiro Chujo[*] and Yuki Takao[†]

Lunar Orbital Platform-Gateway in NASA's Artemis program is expected to provide more opportunities of deep space flight for micro probes or CubeSats in the Sun-Earth-Moon system. To extend lifetime of such small missions saving propellant consumption, solar sails are suitable propulsion systems, applicable to station keeping on libration point orbits and transfer among them. They can also help escaping to the interplanetary region to reach other celestial bodies. This paper shows the design process and some possible examples of solar sailing in the Sun-Earth-Moon system and transfer to the interplanetary region, especially for missions released on Near-Rectilinear Halo Orbit.

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AAS 21-310

ON THE USE OF ZERO-MOMENTUM SURFACES TO IDENTIFY TRANSPORT OPPORTUNITIES TO PLANAR LYAPUNOV ORBITS

Roshan T. Eapen,[*] Kathleen C. Howell,[†] and Kyle T. Alfriend[‡]

Transfer trajectory design in the restricted three-body problem is largely dependent on the topology of the invariant manifolds of a periodic orbit. In this paper, the behavior of such manifolds are studied through the use of a Poincaré map generated from a zero momentum subspace of the third-body motion. Such maps characterize the regions of allowed motions of the invariant manifolds and are shown to occupy the space bounded by quasi-periodic orbits. The dynamical structures arising from these zero-momentum surfaces are utilized to identify transport opportunities to planar Lyapunov orbits develop a catalog of transfers in cislunar space.

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AAS 21-317

THEORY OF LOW-ENERGY TRANSIT ORBITS IN THE PERIODICALLY-PERTURBED RESTRICTED THREE-BODY PROBLEM

Joshua T. Fitzgerald* and Shane D. Ross†

In the circular restricted three-body problem, low-energy transit orbits are revealed by linearizing the governing differential equations about the Lagrange points. This procedure fails when time-periodic perturbations are considered, such as perturbation due to the sun (i.e., the bicircular problem) or orbital eccentricity of the primaries. For the case of a time-periodic perturbation, the Lagrange point is replaced by a periodic orbit, viewed as an index-1 saddle fixed point of a symplectic map, the stroboscopic Poincaré map. In analogy with the geometry about an index-1 saddle equilibrium point, transit and non-transit orbits are identified in the saddle canonical plane. Furthermore, though the continuous time system does not conserve the Hamiltonian energy (which is time-varying), the Poincaré map locally conserves an effective time-independent Hamiltonian function. We therefore demonstrate that the phase space geometry of transit and non-transit orbits is preserved in going from the unperturbed to a periodically-perturbed situation.

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AAS 21-343

DEFINING THE FUNDAMENTAL FREQUENCIES OF QUASI-PERIODIC INVARIANT TORI

Luke T. Peterson[*] and Daniel J. Scheeres[†]

Quasi-periodic orbits are higher-dimensional solutions of Hamiltonian dynamical systems that lie on the surface of invariant tori. Quasi-periodic motion on the torus is fully described by the frequencies of the vector field on the torus; however, any unimodular mapping of the frequency vector offers an equivalent representation. This work presents an approach to uniquely define the frequencies of a quasi-periodic invariant torus. The group-theoretic approach exploits the action of $GL_d(Z)$ on the set of frequencies so that the fundamental frequencies are closest to resonance. Defining fundamental frequencies for quasi-periodic motion unifies computational methods by providing a single identification for these high-dimensional dynamical objects. We include an example applying the theory to center manifolds emanating off of periodic orbits in the Hill three-body problem.

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USING GPUS AND THE PARAMETERIZATION METHOD FOR RAPID SEARCH AND REFINEMENT OF CONNECTIONS BETWEEN TORI IN PERIODICALLY PERTURBED PLANAR CIRCULAR RESTRICTED 3-BODY PROBLEMS*

Bhanu Kumar,† Rodney L. Anderson,‡ and Rafael de la Llave§

When the planar circular restricted 3-body problem is periodically perturbed, most unstable periodic orbits become invariant tori. However, 2D Poincaré sections no longer work to find their manifolds' intersections; new methods are needed. In this study, we first review a method of restricting the intersection search to only certain manifold subsets. We then implement this search using Julia and OpenCL, representing the manifolds as triangular meshes and gaining a 30x speedup using GPUs. We finally show how to use manifold parameterizations to refine the approximate connections found in the mesh search. We demonstrate the tools on the planar elliptic RTBP.

[View Full Paper]

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AAS 21-360

NAVIGATING LOW-ENERGY TRAJECTORIES TO LAND ON THE SURFACE OF EUROPA

Sonia Hernandez,* Rodney L. Anderson,* Duane Roth,* Yu Takahashi,* and Tim McElrath*

The current interest in sending a probe to the surface of Europa in search of life demands not only efficient strategies in mission design, but also requires the capability of knowing the navigability of such types of trajectories. An initial search to find low-energy approach trajectories with a variety of topologies that are challenging to navigate is initially performed in the circular restricted three-body problem. These trajectories are subsequently converted to the ephemeris model and used for detailed navigation analysis. We explore several maneuver strategies and assess spacecraft state uncertainties at Europa arrival as well as fuel consumption.

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AAS 21-363

HYPERCOMPLEX UNIVERSAL VARIABLES APPROACH FOR THE STATE TRANSITION MATRIX IN THE GENERAL KEPLERIAN RELATIVE ORBITAL MOTION

Daniel Condurache*[*] and Vladimir Martinusi[†]

The paper presents a unified approach to the explicit computation of the state transition matrix (STM) associated to the relative orbital motion in Keplerian arbitrary orbits. The use of the hypercomplex universal variables allows the unified formulation of the STM, regardless the elliptic, parabolic or hyperbolic nature of the inertial trajectories. This approach is suitable not only for attractive-type potentials (like the case of the Keplerian motion) but also for Coulomb-like potentials. Last but not least, the universal variables approach is more natural, since it offers a parameterization of the geodesics in the constant curvature phase space on which the inertial motion takes place. The parameterization is made with the help of the generalized trigonometric functions c and s in a space of constant mean curvature.

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SPACE OBJECT CHARACTERIZATION AND INDEPENDENT ATTITUDE DETERMINATION

Session Chairs:

Session 18: Piyush Mehta, West Virginia University

AAS 21-246

MULTI-SCALE CONVOLUTIONAL NEURAL NETWORKS FOR INFERENCE OF SPACE OBJECT ATTITUDE STATUS FROM DETRENDED GEOSTATIONARY LIGHT CURVES

Gregory P. Badura,[*] Christopher R. Valenta,[†] Brian C. Gunter,[‡] and Brian Shoffeitt[§]

Inferring a satellite's operational status and attitude is a critical task in the field of space domain awareness (SDA) to ensure safe space traffic management and minimize the potential for collisions. Photometric light curves of resident space objects (RSOs) can provide information on current operational status by comparing the signal to historical trends as well as extrapolating changes to different dynamics of physical changes in behavior. In this study, 1D convolutional neural network architectures are employed in order to classify simulated geo-stationary (GEO) RSO light curves into one of three operational states: (1) controlled, (2) maneuvering (or station-keeping), or (3) tumbling. Approximately 30,000 full-night light curves of 5 hours in duration were generated using a light curve simulator. The full-night light curves were augmented with approximately 20,000 partial-night light curves of 20-30 minutes in duration that were derived using a window-slicing operation. Two different architectures were trained on the full dataset of full- and partial-night light curves: (1) a Multi-scale Convolutional Neural Network (MCNN), and (2) a deep Convolutional Neural Network (CNN). The MCNN incorporates frequency domain pre-processing and multi-scale feature extraction within the input branches, allowing it to extract oscillations occurring on different timescales. The deep CNN, on the other hand, automates the feature extraction process and has no multi-scale pre-processing operations. The light curves were pre-processed using two different operation schemes prior to training and validation on these architectures: z-normalization of the visual magnitude of the dataset, and z-normalization of the magnitude followed by a detrending to reduce longitudinal phase angle (LPA) effects. Our results show that the MCNN does not out-perform the deep-CNN in terms of F1-score or Matthews correlation coefficient (MCC), suggesting that it is potentially better to choose model architectures that automate the process of feature extraction. Our results also show the LPA trendline removal enhances the performance of both models in terms of F1 and MCC, primarily due to boosts in properly classifying full-night light curves of tumbling RSOs. Finally, our results show that the inclusion of zero-padded and standardized partial-night light curves does not negatively impact the performance of a classifier's performance on full-night light curves, suggesting that datasets can be augmented with incomplete observations.

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AAS 21-283

REAL-TIME, FLIGHT-READY, NON-COOPERATIVE SPACECRAFT POSE ESTIMATION USING MONOCULAR IMAGERY

Kevin Black,[*] Shrivu Shankar,[*] Daniel Fonseka,[*] Jacob Deutsch,[*] Abhimanyu Dhir,[*] and Maruthi R. Akella[†]

A key requirement for autonomous on-orbit proximity operations is the estimation of a target spacecraft's relative pose (position and orientation). It is desirable to employ monocular cameras for this problem due to their low cost, weight, and power requirements. This work presents a novel convolutional neural network (CNN)-based monocular pose estimation system that achieves state-of-the-art accuracy with low computational demand. In combination with a Blender-based synthetic data generation scheme, the system demonstrates the ability to generalize from purely synthetic training data to real in-space imagery of the Northrop Grumman Enhanced Cygnus spacecraft. Additionally, the system achieves real-time performance on low-power flight-like hardware.

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AAS 21-323

LIGHT-ROBUST POLE-FROM-SILHOUETTE ALGORITHM AND VISUAL-HULL ESTIMATION FOR AUTONOMOUS OPTICAL NAVIGATION TO AN UNKNOWN SMALL BODY

Saptarshi Bandyopadhyay,[*] [§] Jacopo Villa,[†] [§] Alan Osmundson,[‡] [§] Benjamin Hockman,[*] [§] Benjamin Morrell,[*] Daniel Lubey,[*] Shyam Bhaskaran,[*] David Bayard,[*] Jay McMahon,[†] [§] Issa A. Nesnas[*]

We present a novel Pole-from-Silhouette (PfS) algorithm, which is robust to non-zero sun phase and illumination conditions like shadows. PfS is an important step in the optical navigation pipeline for an autonomous small spacecraft to approach an unknown small body. The algorithm estimates the rotation pole and 3D shape (visual hull) of a small body using only the illuminated pixels within the silhouette of the small body, the body's rotation rate, the spacecraft attitude, and the spacecraft-target relative distance, which is estimated from orbit determination. We present detailed numerical simulations and multiple sensitivity analyses to demonstrate the effectiveness of our proposed PfS algorithm in different scenarios and target bodies.

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AAS 21-327

EMPIRICAL APPROACHES TO ULTRA-WIDE ANGLE LENS CALIBRATION

Sam Wishnek[*] and Marcus Holzinger[†]

Ultra-wide field-of-view lenses offer unique advantages over narrow field-of-view optical systems in space domain awareness with respect to their ability to observe a large portion of the sky without pointing control. One of the major drawbacks of this technology is the significant distortion induced in the resulting images. Empirical approaches to image calibration to counteract this distortion are investigated for extracting measurements from observations. This allows image calibration to be performed using only the night-sky observations that the optical system regularly collects.

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AAS 21-433

MODELING AND SIMULATION OF ROTARY SLOSHING IN LAUNCH VEHICLES

Jeb S. Orr*

The nonlinear dynamics of propellant sloshing during orbital ascent are usually neglected in the flight control analysis of large boost vehicles under the assumption that the viscous damping of the fluid is sufficient to suppress nonlinear phenomena and confine the fluid to small, planar free surface displacements. In this case, the sloshing dynamics can be modeled using a spring-mass-damper or linearized pendulum mechanical analog. However, large, smooth-wall tanks without significant internal hardware or ring baffles are still susceptible to nonlinear effects. In particular, rotary sloshing can present a risk to flight control as it involves the formation of a stable limit cycle which can lead to undesirable roll coupling. The underlying phenomena of jump resonance does not manifest in linear models, but can be reproduced using a nonlinear spherical pendulum or the Bauer paraboloid model developed during the Apollo/Saturn program. In this paper, a detailed analysis of the rotary sloshing dynamics of these mechanical analogs is presented, and discussed in the context of flight control stability. High-fidelity simulations of a representative boost vehicle are used to verify the semi-analytical predictions of the nonlinear dynamic response.

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SPACE ROBOTICS
AND AUTONOMOUS OPERATION
AND LUNAR

Session Chair:

Session 20: Manoranjan Majji, Texas A&M University, College Station

The following papers were not available for publication:

AAS 21-285 Paper Withdrawn

AAS 21-435 Paper Withdrawn

AAS 21-284

LIBRATION REDUCTION DURING PARTIAL SATELLITE RETRIEVAL OF VERTICAL THREE-MASS TETHERED SYSTEMS

Derek Bourabah* **and Eleonora M. Botta†**

Tether retraction in a three-mass tethered satellite system, when performed without any control algorithm, is an unstable process in which tether libration angle increases over time. A simple control method is proposed to significantly reduce, rather than eliminate, tether libration during a partial retraction maneuver. The proposed control method introduces short periods of extension during retrieval to exploit the Coriolis effect and to efficiently reduce tether libration. Simulations with varying initial conditions and number of extension/retraction cycles in the maneuver phase show that the control algorithm is effective. However, performing the maneuver too many times will diminish the efficiency. Ideally, the proposed methodology is applied to the two connecting tethers. If only one tether is to be controlled, maneuvers on the lower tether have a larger effect on the system's dynamics than maneuvers on the upper tether.

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DESIGN AND ANALYSIS OF DEPLOYMENT MECHANICS FOR A SELF-FOLDING, SPIRAL BASED SPACE-BORNE INTERFEROMETER

Kanak Parmar,[*] Manuel Indaco,[*] Ryan Long,[*] Will Taylor,[†] Nathan Adkins,[‡] Deepika Singla,[‡] Russell W. Mailen,[§] and Davide Guzzetti[§]

Ground based observations of the 21-cm signal to study the cosmological Dark Ages are impeded both by the Earth's atmosphere, as well as man-made radio interference. Therefore, numerous concepts have proposed the use of space-based architectures to observe the 21-cm signal. Previously proposed architectures may be classified into monolithic spacecraft, lunar-based observatories, and satellite formations or swarms. Each architecture type may carry intrinsic shortcomings in cost, complexity, or achievable scientific return. To the series of space-based observatories for 21-cm signal detection, we add a novel concept that utilizes a kilometer-long strip of shape memory polymer (SMP) to actively deploy an orbiting, kilometer-sized, rigidly connected array of antennas in cislunar space. This SMP material will be marked by ink hinges that absorb solar infrared radiation to trigger a temperature gradient and induce folding of the SMP strip into a desired final geometry. If found feasible, this architecture can not only reduce mission complexity, but also decouple the final design from manufacturing and launch constraints, and offer more customizable geometries for interferometry. We currently target a final configuration of a 3 turn spiral with a diameter of 3 km. An appropriate deployment strategy to achieve this configuration is warranted. In this work, we initiated the SMP strip deployment analysis considering both kinematical relations and reduced fidelity dynamical behaviors based on modified double pendulum dynamics. These analyses concluded in the proposal of a sequential deployment strategy, where hinges are activated sequentially. We also consider induction of inertia loads to aid the folding process and reduce the dynamical impact of the increasing moment of inertia of the folded final configuration as deployment progresses.

[View Full Paper]

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AAS 21-337

SUSTAINED LOW-ALTITUDE LUNAR ORBITAL MISSION (SLALOM) NAVIGATION CONCEPT

Jeffrey S. Parker,* Sai Chikine,†
Ethan Kayser,† Charles Cain,† and Matt Bolliger†

This paper describes the navigation system that is being developed to demonstrate the autonomous navigation of a spacecraft traversing an incredibly low-altitude lunar orbit. The Sustained Low-Altitude Lunar Orbital Mission (SLALOM) is a proposed mission concept that would place a spacecraft into an orbit that skims the lunar topographic peaks by 1-5 km and achieves an average topographic height (including basins and craters) of approximately 10 km, sustained for multiple months. The autonomous navigation system includes a collection of onboard orbit determination filters and an autonomous maneuver design system, all of which achieves an onboard, autonomous resiliency to a variety of errors, with contingency plans to rise to safety anytime needed.

[View Full Paper]

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AAS 21-401

METHODS IN TRIANGULATION FOR IMAGE-BASED TERRAIN RELATIVE NAVIGATION

Kevin R. Kobylka* and John A. Christian†

Imagery obtained by a spacecraft in orbit around a celestial body can provide directional measurements from the spacecraft to multiple landmarks on the surface of the body. These measurements may be used to estimate the spacecraft location by triangulation. While there are various non-iterative methods for spacecraft localization, they often create least squares problem with undesirable scaling or error characteristics. This work explores several solutions to the triangulation problem and evaluates their relative efficacy within the context of spacecraft terrain relative navigation (TRN).

[View Full Paper]

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AAS 21-425

NEARLY CONSTANT-TIME SLAM-BASED TERRAIN RELATIVE NAVIGATION FOR LANDING ON AN UNCHARTED WORLD

Matthew W. Givens* and Jay W. McMahon†

Solutions to the Terrain Relative Navigation (TRN) estimation problem have traditionally relied on landmark or image-based maps built from pre-existing orbital imagery to generate absolute position and velocity estimates of a landing vehicle. Insights and advances from the field of Simultaneous Localization and Mapping (SLAM) have produced algorithms that can efficiently estimate both the pose of the vehicle and the environment around it. This work applies one such algorithm, the Exactly Sparse Extended Information Filter (ESEIF), to the TRN problem and compares it to the more traditional Extended Kalman Filter (EKF) approach on the grounds of accuracy and computational efficiency.

[View Full Paper]

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AAS 21-453

POINT MASCON GLOBAL LUNAR GRAVITY MODELS

Sean McArdle[*] and Ryan P. Russell[†]

Lunar gravitational models are generated using sets of point mass potentials fit to the highly resolved GRGM1200A representation derived from GRAIL mission data. Point mass ensembles are highly parallelizable and can encode the gravitational potential and its gradients to an arbitrary order. Iterating on location instead of mass, a new model generation algorithm uses nonlinear optimization to best reproduce the gravitational field. The generated models are intended to be low resolution replacements for spherical harmonics implementations in onboard flight software. The new technique produces models with better numerical stabilities, memory footprints, and evaluation runtimes than previous mascon based models.

[View Full Paper]

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TRAJECTORY OPTIMIZATION

Session Chair:

Session 21: Sonia Hernandez, Jet Propulsion Laboratory

AAS 21-207

QUANTUM-INSPIRED DIFFUSION MONTE CARLO OPTIMIZATION ALGORITHM APPLIED TO SPACE TRAJECTORIES

Federico De Grossi[*] and Christian Circi[†]

In this work, an algorithm for optimization is proposed, inspired by the principles of Quantum Mechanics. The algorithm is based on the Diffusion Monte Carlo method, commonly used for the computation of ground states of many-particles systems. The optimization problem is reconducted to sampling the ground state wave function of a particle subject to a potential based on the function to be minimized. The algorithm is applied to the problem of transfer between circular orbits and compared to the results in the literature. Then it is applied to the problem of rendezvous with the asteroid Pallas and compared to the results of Particle Swarm Optimization algorithm.

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AAS 21-293

GLOBAL OPTIMIZATION OF MANIFOLD-BASED TRANSFERS TO HALO AND BUTTERFLY ORBITS USING HIGHLY-PARALLEL GPU ARCHITECTURE

Yang Foo,[*] Hideaki Ogawa,[†] Satoshi Ueda,[‡] and Mai Bando[§]

Cis-lunar libration point orbits are prime candidates for forthcoming lunar and deep space missions. The present study focuses on transfers between the Earth and highly inclined lunar halo orbits, along with the bifurcated butterfly family via invariant manifolds. Multi-objective genetic optimization has been performed separately employing a *direct* and *hybrid* approach. Surrogates training is incorporated in the former case while the latter relies on a highly-parallel architecture enabled by GPUs (graphics processing units). Pareto-optimal solutions exhibiting different attributes have been identified and representative trajectories are shortlisted. These solutions provide a better understanding of the trade-off between maneuver costs and time, while elucidating interesting dynamical properties in the Moon's vicinity.

[View Full Paper]

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AAS 21-297

OPTIMAL INJECTION INTO QUASI-SATELLITE ORBITS AROUND PHOBOS: APPLICATION TO MMX MISSION

Nicola Marmo,[*] Diogene Alessandro Dei Tos,[†] Hitoshi Ikeda,[‡] and Yasuhiro Kawakatsu[§]

The Japan Aerospace Exploration Agency is aiming to launch in 2024 the Martian Moons eXploration mission. The main scientific objective is to survey the two Martian moons and to return a sample from the surface of Phobos. As nominal scientific orbits, several Quasi-Satellite Orbits around Phobos have been computed and adopted in consideration of the complex dynamical environment characteristic of the Mars–Phobos system. This paper explores the performance capability of a multi-impulsive control strategy to inject the MMX probe into a host of QSOs around Phobos, after a heliocentric journey from the Earth. A perturbation analysis in the vicinity of Phobos is performed using several gravitational models of increasing fidelity. Results show that the CR3BP is a suitable model for this analysis. Finally, a control strategy for the multi-impulsive transfer to Phobos QSOs is presented and, starting from a grid of initial states, optimal QSO injection trajectories are evaluated and discussed.

[View Full Paper]

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AAS 21-318

SPACECRAFT TRAJECTORY-PROPULSION CO-OPTIMIZATION USING ENHANCED REGULARIZED INDIRECT METHODS

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

Application of idealized constant-specific-impulse, constant-thrust electric thruster performance models or curve-fitted polynomials is quite common for spacecraft trajectory design. However, incorporation of realistic performance models of multi-mode electric thrusters leads to notable challenges, and at the same time, offers unprecedented system-level optimization opportunities. In this paper, a framework is developed for co-optimization of 1) spacecraft trajectory, 2) operations modes of multi-mode propulsion systems, and 3) solar array size. The selection of the most optimal operation modes is in accordance to Pontryagin's minimum principle for solving a *payload-mass-maximization* problem. The novelty of the work is further enhanced by solving a mixed-integer problem featuring user-defined constraints on the maximum number of operating modes along the trajectory. Utility of the framework is demonstrated through a multi-year trajectory from Earth to comet 67P/Churyumov–Gerasimenko using an SPT-140 Hall thruster with 21 operating modes; the results are interesting and of significant practical utility.

[View Full Paper]

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AAS 21-404

OPTIMAL MANEUVER TARGETING USING STATE TRANSITION TENSORS WITH VARIABLE TIME-OF-FLIGHT

Spencer Boone[*] and Jay McMahon[†]

This paper presents a methodology for expanding the higher-order state transition tensors (STTs) of a reference trajectory with respect to the final time over which the trajectory is propagated. Following this, a maneuver targeting and optimization scheme with a variable time-of-flight is developed using only the STTs of the reference trajectory, taking advantage of the fact that the first and second-order derivatives of an STT expansion can be obtained analytically. This strategy is applied to a stationkeeping problem for a spacecraft operating in an L1-orbiting halo orbit in the Earth-Moon circular restricted three-body problem. The results show that including a time sensitivity parameter in the STTs allows for more optimal maneuver computation, and can result in improved numerical accuracy. The optimization scheme is very computationally lightweight, and could be suitable onboard use in highly nonlinear dynamical systems.

[View Full Paper]

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AAS 21-407

JUPITER GRAVITY ASSISTS – ANALYTIC APPROXIMATIONS

Ralph L. McNutt, Jr.*

The use of the planet Jupiter to effect gravity assists for aiding propulsive requirements for interplanetary trajectories is well known. In mission proposals and mission planning, typically specific launch opportunities are targets and detailed mission designs developed. However, this approach can be costly in both time and resources if a less specific design space is known. By making use of appropriate, small approximations, we derive general analytic solutions for the performance of both passive and active, i.e., powered, Jupiter gravity assists as a function of initial launch energy and available rocket stage capability during a close flyby of the planet.

[View Full Paper]

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AAS 21-408

COSTATE TRANSFORMATION FOR INDIRECT TRAJECTORY OPTIMIZATION

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

A method is proposed to map costates between two sets of coordinates. The proposed method is suitable for solving optimal control problems using indirect methods and with different sets of coordinates or elements. The Jacobian of the nonlinear map between any two sets of coordinates/elements plays a pivotal role in the costate vector transformation theory. Application of the proposed method and its utility are demonstrated through designing minimum-time and minimum-fuel trajectories.

[View Full Paper]

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FORMATION FLYING

Session Chair:

Session 22: Robert Melton, Pennsylvania State University

SPACECRAFT CLOSE-RANGE TRAJECTORY PLANNING VIA CONVEX OPTIMIZATION WITH GUARANTEED CONVERGENCE

Guoxu Zhang,* Changxuan Wen,† and Dong Qiao‡

This paper demonstrates an iterative algorithm based on convex optimization to solve the spacecraft close-range trajectory planning problem. This problem is constructed as an optimal control problem where path constraints such as thrust boundary constraints and communication no-fly zone constraints are considered, and the optimal fuel or the optimal time is selected as the objective. Then a novel convexification method is proposed. Through the change of the independent variable and the redefinition of variables, the nonlinearity in dynamics is transferred to inequality constraints. Then, through the introduction of intermediate variables, these inequality constraints are decomposed into two parts of concave and convex inequalities. After discretization, the concave inequalities are directly linearized and the original optimal control problem is convexed into a second-order cone programming (SOCP) problem. Then, an iterative solution algorithm is proposed to solve the SOCP problem until convergence. Importantly, the convergence can be guaranteed theoretically. Numerical examples show the effectiveness and efficiency of the proposed algorithm.

[View Full Paper]

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AAS 21-287

DISTRIBUTED PATH PLANNING METHOD FOR LARGE-SCALE SWARM SAFE MIGRATION

Xingyu Zhou,* Dong Qiao,† Changxuan Wen,‡ and Hongwei Han§

Recently, there has been a tremendous increase of interest in utilizing large-scale swarm for potential space application. Swarm systems are inherently safety-critical systems since safety guarantees (e.g., collision avoidance) must be ensured during migration. The number of collision avoidances increases in a quadratic relationship with the number of spacecraft in a swarm, leading to a computationally expensive large-scale nonlinear programming problem. To efficiently solve this problem, this paper proposes a distributed sequential convex optimization (DSCO) method for large-scale fuel-optimal swarm migration problems. The optimal control problem (OCP) under collision avoidance constraints is formulated. The coupled collision avoidance constrains are decoupled in an iterative framework based on the nominal trajectory. Specially, two treatments are executed to improve the efficiency and robustness of the algorithm. Then sequential convex programming (SCP) is used to solve the distributed sub-problems. Finally, the proposed DSCO is successfully applicated to a 100-spacecrafts swarm migration problem.

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AAS 21-341

NONLINEAR MAPPING OF ORBIT ELEMENT DIFFERENCES FOR SPACECRAFT FORMATION FLYING

Ayansola D. Ogundele[*] and Olufemi A. Agboola[†]

The increase in interest on spacecraft formation flying concept necessitated the need to design and develop a high fidelity dynamical models for future space missions. Generally, the relative motion dynamic model is developed using Hill frame coordinates. But, unlike in the case of Hill coordinates involving the use of six relative orbit invariants for defining spacecraft relative orbit, using orbit element differences for the relative motion analysis only the time varying true latitude, out of the six orbital elements, needs to be tracked and there is no need for the linearizing assumptions and near circular chief orbit requirements. In this paper, to improve the dynamics fidelity, higher order relative motion model is developed using orbit element differences. The nonlinear mapping between orbit element differences and Hill coordinates are established via second order variation expansion technique of variation of calculus method. Using the nonlinear mapped relationship, radial, along-track and cross-track positions and velocities are developed. Also, nonlinear evolution of true latitude was developed and from it linearized spacecraft relative motion in terms of orbit elements are obtained. Afterward, analytical solution of the linearized equation was developed. Through numerical simulations, a comparison is made with the existing models and the results show a better performance using the new nonlinear mapped relative motion.

[View Full Paper]

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AAS 21-348

SATELLITE FORMATION RECONFIGURATION AND THE TRAVELING SALESMAN PROBLEM

Kyle T. Alfriend* and Mark Karpenko†

The problem being investigated is: Given a formation of m satellites and a set of N formations from a group of formations develop a methodology for determining an optimal sequence for visiting each formation such that the total impulsive Δv required for the set of reconfigurations is minimized. It is shown that the solution reduces to a Traveling Salesman Problem (TSP) using a Manhattan (L1) norm. With N formations there are N points and the axes are the in-plane and out-of-plane Δv's for achieving the reconfiguration from the initial formation. Insights from a new TSP theory are used to solve the problem.

[View Full Paper]

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AAS 21-373

CLOSED FORM SOLUTION OF NONLINEAR J_2 PERTURBED SPACECRAFT FORMATION FLYING IN ELLIPTICAL ORBIT

Ayansola D. Ogundele* **and Olufemi A. Agboola†**

In this paper, a new approximation of nonlinear J2 perturbed spacecraft formation flying dynamics, in elliptical orbit, with quadratic nonlinear terms is developed. Afterward, the approximated equation was normalized to produce true-anomaly varying equation amenable for the application of power series method which is one of the most widely used and powerful analytic methods for constructing solutions of linear and nonlinear differential equations. Then, new closed form, power series solution of the relative motion was developed. As shown by the numerical simulations, the new power series solution of the approximated J2 perturbed relative motion with quadratic nonlinear terms compared favorably with the nonlinear J2 perturbed motion. The new solution is useful for spacecraft formation flying analysis, proximity operations and rendezvous purposes.

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AAS 21-448

SPACECRAFT SWARM APPLICATIONS FOR MONITORING ACTIVE EARTH FEATURES

Ravi teja Nallapu,[*] Yinan Xu,[†] and Jekanthan Thangavelautham[‡]

The planet Earth is characterized by a wide variety of features that exhibit unique physical, chemical, and dynamical characteristics. Specifically, active features such as volcanoes hold critical information regarding the local composition. They are also important for security purposes to enable proactive emergency evacuations in case of an impending eruption. Therefore, understanding the natural and human-induced consequences of such processes are known to have a critical impact on society, economy, and technology development. However, traditional environment monitoring satellites tend to be large and expensive. The advancement of low-cost small spacecraft technology has opened a new paradigm of Earth observation by deploying Earth monitoring sensor networks on small spacecraft constellations. In a rapidly changing world, high-resolution, timely geospatial information with global access and coverage become increasingly important. Unlike traditional radar systems, synthetic aperture radar (SAR) can observe through clouds, haze, and the dark and analyze change on the ground, regardless of the weather conditions of the day. While swarm architectures, such as constellations, provide crucial tools to study Earth-based features, an automated design architecture to maximize their synergistic returns is yet to be realized. In our previous work, we developed IDEAS, an end-to-end software to design spacecraft missions. IDEAS uses Evolutionary Algorithms to automate the design of spacecraft, swarm, and their launch trajectories. The IDEAS framework has been used to design reconnaissance missions to small bodies, enable detection of incoming meteors, and enable communication in the cis-lunar space. This work will focus on enabling IDEAS to design swarm missions for monitoring active Earth features with SAR sensing. To achieve this, we develop spatial and probabilistic coverage evaluation algorithms for different operational modes of a SAR sensing spacecraft to detect the active features. The coverage evaluation algorithms will be used to design the spacecraft swarm. The seed spacecraft will then be used to design a constellation that maximizes the spatial coverage of the swarm. Finally, we demonstrate the algorithms developed in this work, using a numerical case study to design a SAR-based swarm to detect volcanoes. The results indicate the successful performance of the designed swarms with SAR sensing architectures for Earth Monitoring, which will significantly improve the first response of the Earth events.

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AAS 21-451

SPACECRAFT FORMATION CONTROL NEAR A PERIODIC ORBIT USING GEOMETRIC RELATIVE COORDINATES

Ian Elliott[*] and Natasha Bosanac[†]

A feedback control law is introduced for spacecraft relative motion near a periodic orbit with an oscillatory mode in the circular restricted three-body problem. The control law feeds back errors expressed using a geometric relative coordinate set that describes a state relative to a periodic orbit with respect to nearby first-order approximations of invariant tori. This tracking error definition enables the straightforward design of reference trajectories for formation flying on quasi-periodic orbits and gain selection based on geometric insight. Numerical simulations apply the controller to stabilize a spacecraft on a torus relative to a periodic orbit for low control effort.

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GUIDANCE, NAVIGATION, AND CONTROL

Session Chair:

Session 23: Marcus Holzinger, University of Colorado Boulder

The following paper was not available for publication:

AAS 21-397 Paper Withdrawn

AAS 21-260

OPTIMAL REFERENCE ORBIT TRACKING AROUND ASTEROIDS VIA PARTICLE SWARM OPTIMIZATION AND INVERSE DYNAMICS TECHNIQUE

Andrea D'Ambrosio,[*] Andrea Carbone,[†] Marco Mastrofini[‡] and Fabio Curti[§]

Optimal proximity maneuvers are essential to obtain accurate space missions. Indeed, they are extremely important in perturbed environments, such as around asteroids, where the gravity field is very irregular because of the irregular shapes. For this same reason, gravity field estimation is also very challenging. This paper focuses on optimal control of proximity maneuvers obtained thanks to the combination of Particle Swarm Optimization, inverse dynamics technique and B-spline curves, used to approximate the trajectory. Furthermore, an Extreme Learning Machine-based algorithm is employed to estimate the gravity vector from the position vector in the asteroid body-fixed frame. This choice allows to achieve a good accuracy while decreasing at the same time the computational time that other precise methods, like the polyhedron model, would require. Finally, the proposed framework is applied to reference orbit tracking around asteroid 951 Gaspra.

[View Full Paper]

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AAS 21-347

DIRECT VISUAL SLAM WITH A FILTER-BASED LIDAR MEASUREMENT INCORPORATION

Corey Marcus[*] and Renato Zanetti[†]

In this paper we present a Direct Monocular SLAM system which is augmented with flash LIDAR images. The LIDAR measurements are incorporated with an Extended Kalman Filter and utilization of the Gamma and Inverse Gamma probability distribution functions. The system produces metric pose and map estimates. Monte Carlo methods are used to demonstrate that incorporating LIDAR measurements into the system provides significant performance improvements over a system without LIDAR in simulation. Experimental results using the EuRoC dataset are then presented which show improved system performance in real-time operation.

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AAS 21-353

COVARIANCE ESTIMATION USING GEOMETRIC OPTIMIZATION ON SYMMETRIC POSITIVE DEFINITE MANIFOLDS

Rahul Moghe,[*] Maruthi R. Akella,[†] and Renato Zanetti[‡]

This paper provides a significant extension to our previous work on adaptive covariance estimation that estimates the noise covariance matrices of a discrete linear system with simultaneous guarantees for convergence of the noise covariance estimates and the state estimates. The specific advance established in this work is that the estimates of the covariance are calculated using a differential geometric optimization framework that ensures that the covariance estimates lie restricted to the symmetric positive definite (SPD) manifold. This property is desirable since the covariance estimates used in calculating the state estimates have to be SPD at all times for them to be meaningful. A cost function that is geodesically convex on the SPD manifold is chosen to provide a globally optimal solution.

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AAS 21-366

ORBIT MAINTENANCE STRATEGY FOR EARTH-MOON HALO ORBITS

Vivek Muralidharan* **and Kathleen C. Howell†**

The L1 and L2 Near Rectilinear Halo Orbits (NRHOs) are proposed long horizon trajectories for cislunar exploration missions. Due to unmodeled forces as well as orbit determination errors in this dynamically sensitive region, the spacecraft deviates from the desired path. The current investigation focuses on an extended analysis of an impulsive stationkeeping technique to maintain the spacecraft near a long horizon virtual reference orbit. The dynamics in the halo orbit region are explored to identify suitable maneuver and target locations for stationkeeping. Furthermore, phasing constraints are incorporated to maintain spacecrafts on orbit where position and velocity states are sensitive to epoch time.

[View Full Paper]

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AAS 21-416

ESTIMATION OF THE CONDITIONAL STATE AND COVARIANCE WITH TAYLOR POLYNOMIALS

Simone Servadio[*] and Renato Zanetti[†]

A novel estimator is presented that expands the typical state and covariance update laws of Kalman filters to polynomial updates in the measurement. The filter employs Taylor series approximations of the nonlinear dynamic and measurement functions. All polynomials (functions approximation, state update, and covariance update) can be made to arbitrary order to trade between filter's accuracy/consistency and computational time. The performance of the algorithm is tested in numerical simulations.

[View Full Paper]

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AAS 21-439

ORION GN&C SEQUENCING FOR OFF-NOMINAL RENDEZVOUS, PROXIMITY OPERATIONS, AND DOCKING

Jordan S. Abell,[*] Peter Z. Schulte,[†] Fred D. Clark,[‡] Peter T. Spehar,[§] and David C. Woffinden[§]

This paper discusses the Concept of Operations of the nine contingency strategies available for off-nominal Rendezvous, Proximity Operations, and Docking of Orion with the Gateway in a Near-Rectilinear Halo Orbit around the Moon. Explanations are provided for each contingency strategy, how they are initiated, when they can be initiated, and how they are designed to protect the crew. Then an overview is provided of the sequencing of the Guidance, Navigation, and Control flight software used to achieve each contingency strategy, in the form of Phases, Segments, Activities, and Modes. These off-nominal scenarios require the definition of new Segments and Activities.

[View Full Paper]

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ORBIT DETERMINATION

Session Chair:

Session 24: Kyle DeMars, Texas A&M University

PROCESS NOISE COVARIANCE MODELING FOR ABSOLUTE AND RELATIVE ORBIT DETERMINATION

Nathan Stacey* and Simone D'Amico†

This paper develops new analytical process noise covariance models for both absolute and relative orbit determination in a discrete-time Kalman filtering framework. Process noise is always present in orbit determination due to dynamics modeling deficiencies, and accurately modeling this noise is essential for optimal estimation. A common approach called state noise compensation models process noise as zero-mean Gaussian white noise accelerations. The resulting process noise covariance can be evaluated numerically, which is computationally intensive, or through a widely used analytical model that is restricted to a Cartesian state and small propagation intervals. Moreover, mathematically rigorous, analytical process noise covariance models for relative spacecraft states are not currently available. To address these limitations of the state of the art, new analytical process noise covariance models are developed for state noise compensation for both Cartesian and orbital element state representations. Two frameworks are then presented for modeling the process noise covariance of relative spacecraft states by assuming either small or large interspacecraft separations. The presented techniques are validated through numerical simulations.

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AAS 21-280

COMPARISON AND ERROR MODELING OF VELOCITY-BASED INITIAL ORBIT DETERMINATION ALGORITHMS

Linyi Hou,* Kevin Lohan,† and Zachary R. Putnam‡

Recently, Christian and Hollenberg proposed and solved a new class of initial orbit determination problems based only on velocity measurements.[1, 2] We introduce a modification to the velocity-based initial orbit determination algorithm to improve accuracy and computational efficiency. Orbit determination error trends with respect to semi-major axis, eccentricity, initial true anomaly, and sensor noise are modeled using the orbit hodograph, and verified using Monte Carlo simulations. An example is provided to show that error trend models can accurately predict the error of hodograph-based velocity initial orbit determination algorithms.

[View Full Paper]

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AAS 21-309

TOWARDS ACCURATE ORBIT DETERMINATION USING SEMI-ANALYTICAL SATELLITE THEORY

Bryan Cazabonne[*] and Paul J. Cefola[†]

Space agencies generally use numerical methods to meet their orbit determination needs. Due to the ever increasing number of space objects, the development of new orbit determination methods becomes essential. DSST is an orbit propagator based on a semi-analytical theory. It combines the accuracy of numerical propagation and the speed of analytical propagation. The paper presents an open-source DSST orbit determination application included in the Orekit library. Accuracy of the DSST orbit determination is demonstrated by comparison with a numerical method. Both the satellite's state vector estimation and the measurement residuals are used as comparison metrics.

[View Full Paper]

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AAS 21-314

NONLINEAR SET-MEMBERSHIP FILTERING-BASED ORBIT ESTIMATION

Diganta Bhattacharjee* **and Kamesh Subbarao†**

We propose a nonlinear set-membership filtering-based orbit estimation technique for Earth-orbiting satellites or space objects. The recursive set-membership filter utilizes the state dependent coefficient parameterization to acquire a pseudo-linear description of the governing nonlinear system. At every recursion, the filter requires solutions to two convex optimization problems and these solutions can be efficiently obtained. We have provided details of the filter design, the nonlinear motion model for the satellite or space object in orbit, and the measurement model. A simulation example is included to illustrate the effectiveness of the proposed approach. Furthermore, estimation results of the set-membership filter are compared with those of an extended Kalman filter, which demonstrate that the set-membership filter outperforms the extended Kalman filter for the simulation example considered.

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AAS 21-326

OPTIMALLY CONVERGENT MINIMUM-TIME SPACE OBJECT SEARCH AND RECOVERY

Samuel J. Fedeler,[*] Marcus J. Holzinger,[†] and William Whitacre[‡]

A critical challenge in Space Domain Awareness (SDA) is gaining custody of newly detected or maneuvering objects. The dynamically feasible location of one such object may be represented as an admissible region or reachable set. This paper proposes techniques for exploring search sets using sample-based planning. Several methods for sampling feasible regions of measurement space are developed, and Monte Carlo Tree Search (MCTS) is applied over a limited horizon to determine time-optimal sets of actions. Tree search aids in overcoming local minima in solutions found with traditional optimization methods.

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AAS 21-338

ORBIT DETERMINATION VIA PHYSICS INFORMED NEURAL NETWORKS

Andrea Scorsoglio[*] and Roberto Furfaro[†]

In this paper, a new method for solving orbit determination problems is introduced named Physics Informed Least Squares (PILS). We use a particular kind of single layer feed-forward neural networks called Extreme Learning Machines to enable higher accuracy and flexibility than classical least squares. The least squares estimate is used as baseline for the loss function, to which a regularizing term based on the differential equations modelling the dynamics of the problem is then added. This ensure that the learned relationship between input and output is compliant with the physics of the problem. The results are comparable or better than the batch least squares solution, with the advantage of not requiring an initial guess and being able to solve for the complete trajectory without needing any integration.

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AAS 21-362

THE IMPROVEMENT OF SATELLITE CONSTELLATION GNSS ORBIT DETERMINATION THROUGH THE INCORPORATION OF INTERSATELLITE RANGING MEASUREMENTS

Byron Davis* **and Brian C. Gunter†**

For many satellite remote sensing and communications missions, particularly those involving a formation or constellation of satellites, having precise knowledge of the satellite's position in both an absolute and relative sense is essential. However, the capabilities of Global Navigation Satellite Systems (GNSS)-based precise orbit determination (POD) alone may not be enough to support the application needs. This work examines potential gains to POD when additional Intersatellite Range (ISR) observations are combined with standard GNSS observables. The methodology behind the combination approach is described and illustrated through a series of simulated case studies involving two or more satellites in low Earth orbit (LEO) using realistic, hardware derived (where possible), measurement noise. The results suggest that substantial (nearly a factor of 2) improvement in the POD for all satellites in the constellation can be obtained with even intermittent ranging measurements. In addition, the precision of the ISR measurements were limited, with additional constraints on the ISR distance, to represent levels possible from current CubeSat systems. By improving the positioning capabilities of CubeSat constellations, new Earth observing missions utilizing CubeSat constellation architectures will become feasible. In addition, the procedure presented can be generalized to other hardware and ISR methodologies.

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ORBITAL DYNAMICS, PERTURBATIONS AND STABILITY

Session Chair:

Session 25: Diane Davis, a.i. solutions, Inc.

AAS 21-233

INCLUDING THE CLOSED-FORM J_2^2 EFFECT IN DSST

Juan F. San-Juan,[*] Rosario López,[†] Iván Pérez[‡] and Paul J. Cefola[§]

A second-order closed-form semi-analytical solution of the main problem of the artificial satellite theory (J_2 contribution) consistent with the Draper Semi-analytic Satellite Theory (DSST) is presented in Delaunay variables. The short-period terms are removed using an extension of the Lie-Deprit method. The averaged equations of motion are given explicitly and transformed into the non-singular equinoctial elements. Finally, the second-order terms in the equations of motion are included in the C/C++ version of the DSST orbit propagator.

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AAS 21-240

KOOPMAN OPERATOR THEORY APPLIED TO THE J2 PERTURBED MOTION AROUND AN OBLATE PLANET

David Arnas[*] and Richard Linares[†]

This work focuses on the generation and study of approximated analytical solutions to the J2 perturbed problem of a satellite orbiting the Earth. This is done by using a new set of variables based on spherical coordinates to fully represent the J2 dynamics, and the Koopman operator perturbation theory to solve the system of differential equations that defines the problem. In that regard, this manuscript includes a description of the methodology applied to the J2 perturbed problem as well as a study of the performance of the proposed methodology for different orbits.

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AAS 21-303

MODERN NUMERICAL PROGRAMMING WITH JULIA FOR ASTRODYNAMIC TRAJECTORY DESIGN

Dan Padilha,[*] Diogene A. Dei Tos,[†] Nicola Baresi,[‡] and Junichiro Kawaguchi[†]

A programming toolkit is developed to leverage Julia, a high-performance numerical programming language, in the generation, optimisation, and analysis of orbital trajectories. Julia combines high-level abstraction with the computational efficiency of dynamic compilation, enabling highly composable and extensible programs and state-of-the-art performance in differential systems, statistical analysis, and machine learning. This paper outlines the motivations and consequences of Julia's multiple dispatch, meta-programming, and other capabilities, and demonstrates techniques enabled for future development of astrodynamics toolkits. The resulting `OrbitalTrajectories.jl` toolkit's composability, extensibility, and performance is compared to JAXA's in-house *jTOP* trajectory propagation and optimisation tool, outperforming it by up to an order of magnitude in ephemeris-based restricted *N*-body trajectory propagation.

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AAS 21-335

THE TERRESTRIAL EXOPLANET SIMULATOR: AN ORBITAL PROPAGATOR WITH OPTIMAL ERROR GROWTH FOLLOWING BROUWER'S LAW

Peter Bartram[*] and Alexander Wittig[†]

We present the Terrestrial Exoplanet Simulator (TES), a new n-body integrator for propagating systems dominated by a central mass that permits close encounters and follows Brouwer's law for over a billion orbits. That means we can maintain a relative energy error at machine precision, i.e. 10–16, for 105 orbits and achieve a precision of 10–14 after 108 orbits. To achieve this, TES refines the classical Encke method with a series of numerical improvements that reduce both integration runtime and numerical error. We show that the performance of TES is highly favourable for long-term evolution and that close encounters of near Earth objects, such as Apophis, are propagated precisely. TES can be extended to support arbitrary perturbing forces, making it suitable for highly accurate long-term integration of satellites in the LEO environment.

[View Full Paper]

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AAS 21-352

ENERGY AND PHASING CONSIDERATIONS FOR LOW-ENERGY TRANSFERS FROM CISLUNAR TO HELIOCENTRIC SPACE

Kenza Boudad,[*] Kathleen Howell,[†] and Diane Davis[‡]

In the next decades, multiple missions are proposed or planned that originate in the vicinity of the Moon and are to be delivered to heliocentric space, such as servicing missions to the Nancy Roman or the James Webb Space Telescopes, as well as departures from Gateway to other interplanetary destinations. The Earth-Moon-Sun transit dynamics are complex, primarily influenced by the Earth and the Moon in cislunar space; the gravitational influence of the Sun becomes significant after departure from the Earth-Moon vicinity. The current investigation leverages an Earth-Moon-Sun-spacecraft four-body model, that is, the Bicircular Restricted Four-Body Problem, including dynamical structures in this regime such as periodic orbits and manifolds, to design low-energy transfers from the cislunar space to the heliocentric orbits near the Sun-Earth $\underline{L}_1$ and $\underline{L}_2$ portals.

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AAS 21-365

AN ANALYSIS OF KOOPMAN-BASED PERTURBATION THEORY APPLIED TO THE MOTION ABOUT AN OBLATE PLANET

David Arnas,[*] Richard Linares,[†] and Kyle T. Alfriend[‡]

This manuscript analysis the solution provided by the Koopman operator methodology in its application to the main satellite problem. In this regard, this work performs an spectral study of the solution generated and compares it with the solution provided by the Poincaré-Lindstedt method. In addition, this manuscript introduces a perturbation methodology based on the Koopman operator to study perturbed systems. This new technique allows to obtain the perturbed frequencies and associated perturbed eigenfunctions of the system using the solution of the unperturbed problem, which reduces the amount of computations required to generate the solution. Several examples of application of these methodologies are included to show their performance under different conditions.

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AAS 21-375

SRP-J2 RESONANCES IN LOW EARTH ORBITS FOR OBJECTS WITH A TIME-VARIANT AREA-TO-MASS RATIO

Catherine Massé,[*] Inna Sharf,[†] and Florent Deleflie[‡]

In this work, we study the effect of the rotational motion on the SRP-J2 resonance phenomenon and we suggest that a resonance effect of considerable strength could be achieved for non-spherical spacecraft in any orbit, by adopting an appropriate rotational motion scenario. In this way, it would be possible for a spacecraft to exploit the resonance to accelerate its de-orbitation. Using Gauss' singly-averaged planetary equations, we present a derivation of rotation scenarios that would generate a resonance, followed by simulation results verifying this analysis, as well as a detailed analysis of the phase plots to provide more insight into the eccentricity evolution.

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GUIDANCE AND CONTROL

Session Chair:

Session 27: Atri Dutta, Wichita State University

AAS 21-208

AUTONOMOUS SPACECRAFT OBSTACLE AVOIDANCE AND TRAJECTORY TRACKING IN DENSE DEBRIS FIELD

Madhur Tiwari,* David Zuehlke,† Troy Henderson‡ and Richard J. Prazenica§

In this paper, we implement an autonomous path planning technique using artificial potential functions paired with a direct adaptive controller for spacecraft trajectory tracking through a dense debris field. The debris field is modeled as fixed debris and the spacecraft is modeled using relative orbital dynamics with disturbances. The spacecraft is assumed to be in proximity to a dense debris field that it must navigate through to reach a goal destination. Obstacle avoidance trajectories are generated using model independent artificial potential functions that rely only on the position measurements of the debris with respect to the spacecraft. A direct adaptive controller is implemented to track generated trajectories because it can achieve robust tracking in the presence of model and path uncertainties.

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AAS 21-258

CLASS OF OPTIMAL SPACE GUIDANCE PROBLEMS SOLVED VIA INDIRECT METHODS AND PHYSICS-INFORMED NEURAL NETWORKS

Enrico Schiassi,[*] Andrea D'Ambrosio,[†] Andrea Scorsoglio,[‡] Roberto Furfaro,[§] and Fabio Curti[**]

In this paper, a class of optimal space guidance control problems is solved using the combination of indirect method and Physics-Informed Neural Networks (PINNs). More specifically, we consider the class of optimal control problems with integral quadratic cost. The boundary value problems that arise from the application of the Pontryagin Minimum/Maximum Principle are solved via PINNs, which are particular neural networks where the training of the network is driven by the physics of the problem, modeled through Differential Equations. Three different PINN frameworks are considered, the standard PINN, the Physics-Informed Extreme Learning Machine (PIELM), and Physics-Informed Extreme Theory of Functional Connections (X-TFC). The main difference between standard PINN and PIELM with X-TFC is that with X-TFC initial and boundary conditions are analytically satisfied thanks to the so-called Constrained Expressions, introduced with the original Theory of Functional Connections (TFC). These expressions are a sum of a free-function, expanded as a single layer neural network trained via Extreme Learning Machine (ELM) algorithm, and a functional that analytically satisfies the boundary constraints. The results of this paper show the convenience of employing PINN frameworks to tackle this class of optimal control problems, especially PIELM and X-TFC, as they provide very good accuracy with low computational times.

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AAS 21-259

PHYSICS-INFORMED NEURAL NETWORKS APPLIED TO A SERIES OF CONSTRAINED SPACE GUIDANCE PROBLEMS

Andrea D'Ambrosio,[*] Enrico Schiassi,[†] Fabio Curti,[‡] and Roberto Furfaro[§]

The newly developed method named Extreme Theory of Functional Connections, or X-TFC, is exploited in this paper to solve constrained optimal control problems. This framework belongs to the family of Physics-Informed Neural Networks (PINNs), and it exploits the so-called Constrained Expressions (CEs) to approximate the latent (unknown) solutions. These expressions, developed within the Theory of Functional Connections (TFC) framework, are the sum of a free-chosen function, and a functional that always analytically satisfies the boundary conditions. According to the X-TFC method, the free function is a single layer neural network trained via Extreme Learning Machine (ELM) algorithm. Optimal control problems are treated via indirect method, based on the Hamiltonian of the problem and the Pontryagin Minimum Principle to obtain the optimal control and the first order necessary conditions. Within this formulation, inequality constraints are considered by introducing new variables and additional terms in the cost function, and in the Hamiltonian. Moreover, saturation functions are used to consider the boundaries of inequality constraints. X-TFC is then employed to solve the boundary value problem that arises from the indirect method. Since the boundary conditions are a priori satisfied, accurate results are obtained with a low computational time.

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AAS 21-386

REACTION WHEEL VIBRATIONAL JITTER META-ANALYSIS: INTEGRATIVE INSIGHTS VIA STATISTICAL CORRELATIONS

Martin D. Hasha*

Reaction Wheel Assemblies (RWAs) enable precise sustained spacecraft Line-of-Sight (LOS) stability. Fine-pointing budgets manage RWA Induced Vibrations (IV) threats to jitter via structured error allocations. Adjudicated limits are handicapped due to a lack of statistically-significant data: levels/margins are often unnecessarily large to address uncertainties. By enlisting data science approaches, a multifaceted investigation tackles data mining of unique aggregates of high-performance flight-accepted datasets: same-family duplex-bearing-design (like-tested) large progenitor (25) plus midsized contemporary (26) RWAs. IV directionality, harmonics, and root source data analytics employ bivariate correlations, via Pearson's coefficients, for many key parameters to ferret out previously unknown or unresolved relationships. Proven optimization methodologies are discussed that meet stringent LOS stability levels. Data results, key issues, lessons learned, and limit-balancing tradeoffs are highlighted: insights found are of utmost value to LOS jitter modeling/analyses. Experience in improved precision balancing, versus extended bearing screenings, is presented. Prior meta findings are expanded to apply to future RWAs. Approaches readily adapt to a wide breadth of rotating/dithering space platform contexts: steering mirrors, cryocoolers, moving antenna, micro-g platforms, object flybys, etc.

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AAS 21-402

PRECISION ATTITUDE STABILIZATION WITH INTERMITTENT EXTERNAL TORQUE

S. P Arjun Ram* and Maruthi R Akella†

The attitude stabilization of a micro-satellite employing a variable-amplitude cold-gas thruster which reflects as a time varying gain on the control input is considered. Existing literature uses a persistence filter based approach that typically leads to large control gains and torque inputs during specific time intervals corresponding to the “on” phase of the external actuation. This work aims at reducing the transient spikes placed upon the torque commands by the judicious introduction of an additional time varying scaling signal as part of the control law. The time-update mechanism for the new scaling factor and overall closed-loop stability are established through a Lyapunov-like analysis. Numerical simulations highlight the various features of this new control algorithm for spacecraft attitude stabilization subject to torque intermittence.

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AAS 21-441

PERCEPTRON BASED ORBITAL GUIDANCE IN A LOW GRAVITY ASTEROID ENVIRONMENT

Leonard D. Vance[*] and Jekan Thangavelautham[†]

The discovery that the near-Earth asteroid (101955) Bennu is regularly ejecting particles into space changes our fundamental understanding of rubble pile asteroids. This suggests that future sample and return missions could capture such particles in flight, eliminating the significant risks associated with the mission spacecraft touching down to actively gather material on the asteroid surface. Observed particle ejection events typically produce dozens of objects with flight times typically measured in hours, so multiple nanospacecraft are advisable, allowing particle capture in parallel. With limited computational capability, such Nanospacecraft must develop simplified guidance techniques which can be implemented within their limited form factor.

The universal variables solution to Lambert's problem provides a computational algorithm for orbital maneuvering under the influence of a single gravitational body, however, the solution is iterative and relatively computationally expensive. This paper shows that a perceptron based neural network can be trained to substitute for Lambert based guidance, providing a low computational cost guidance alternative. The resulting neural network is specifically optimized for the mission of collecting ejected particles from a rubble pile asteroid, but the overall technique can be applied to the wider application of general orbital maneuvering. Derivation of a training set is followed by establishment of an error minimization algorithm, leading to training epochs which result in delta V commands which can be directly compared to actual values as derived through Lambert's solution. A closed loop simulation of intercept trajectories with mid-course updates is then executed to gain an understanding of in-flight performance.

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SPACE ROBOTICS AND AUTONOMOUS OPERATION

Session Chair:

Session 29: Jay McMahon, University of Colorado Boulder

The following papers were not available for publication:

AAS 21-213 Paper Withdrawn

AAS 21-224 Paper Withdrawn

AAS 21-382 Paper Withdrawn

AAS 21-238

GENETIC FUZZY SYSTEM-BASED MULTI-ROBOT COORDINATION FOR PLANETARY MISSIONS

Daegyun Choi[*] and Donghoon Kim[†]

This paper proposes a decentralized approach for a multi-robot system (MRS) using a genetic fuzzy system to perform a collaborative object transportation task that minimizes the total path length of the MRS in unstructured environment while avoiding obstacles. For an environment given by an elevation map, terrain traversability analysis with respect to the slope is performed to reduce the dimension and identify non-traversable areas that can be considered as obstacles, and the given map is converted into a traversability map in two dimensional space. In the training process, proposed fuzzy inference systems (FISs) to generate the MRS's velocity for transporting an object to a target position are optimized by a genetic algorithm with several scenarios, such as a local minima, a target that is close to an obstacle, and a cluttered environment. The trained FIS models are applied to the testing environment, which is the converted traversability map, and validated using multiple scenarios.

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AAS 21-421

SAFE AND UNCERTAINTY-AWARE ROBOTIC MOTION PLANNING TECHNIQUES FOR AGILE ON-ORBIT ASSEMBLY

Bryce Doerr,[*] Keenan Albee,[†] Monica Ekal,[‡] Richard Linares,[§] and Rodrigo Ventura[**]

As access to space and robotic autonomy capabilities move forward, there is simultaneously a growing interest in deploying large, complex space structures to provide new on-orbit capabilities. New space-borne observatories, large orbital outposts, and even futuristic on-orbit manufacturing will be enabled by robotic assembly of space structures using techniques like on-orbit additive manufacturing which can provide flexibility in constructing and even repairing complex hardware. However, the dynamics underlying the robotic assembly system during manipulation may operate under uncertainties (e.g. changing inertial properties). Thus, inertial estimation of the robotic assembler and the manipulated additively manufactured component must be considered during the structural assembly process. The contribution of this work is to address both the motion planning and control for robotic assembly with consideration of the inertial estimation of the combined free-flying robotic assembler and additively manufactured component system. Specifically, the Linear Quadratic Regulator Rapidly-Exploring Randomized Trees (LQR-RRT*) and dynamically feasible path smoothing are used to obtain obstacle-free trajectories for the system. Further, model learning is incorporated explicitly into the planning stages via approximation of the continuous system and accompanying reward of performing safe, objective-oriented motion. Remaining uncertainty can then be dealt with explicitly via robust tube model predictive control techniques. By obtaining controlled trajectories that consider both obstacle avoidance and learning of the inertial properties of the free-flyer and manipulated component system, the free-flyer rapidly considers and plans the construction of space structures with enhanced system knowledge. The approach naturally generalizes to repairing, refueling, and re-provisioning space structure components while providing optimal collision-free trajectories under e.g., inertial uncertainty.

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CATALYST: A PLATFORM FOR AUTONOMOUS DOCKING, TETHERING AND MULTI-SPACECRAFT AGGREGATION

Jekan Thangavelautham,* Himangshu Kalita,† and Leonard Vance‡

Significant advances have been made in the miniaturization of robotic hardware, particularly sensors, actuators, and computers. This has spawned lightweight, highly dexterous robots that have the potential to match and exceed human physical capabilities in space and planetary environments. However, this miniaturization trend has not been fully exploited to enable satellites to perform complex never before seen maneuvers with robotic spacecraft. These potential maneuvers can enable high-risk, high-reward science or take on challenging tasks where the outcome has low probability of success. All of these factors can benefit from utilization of a demonstration platform that can help derisk precise attitude control maneuvering, docking, aggregation and tethering of nano-spacecraft. Such an advancement can put these nano-spacecraft on a path to increasing their reliability and performance to compete against large monolithic spacecraft architectures. Here we propose an experimental platform called Catalyst to advance small spacecraft architectures that can perform precise attitude maneuvers, docking, tethering, aggregation into larger more-capable satellite. This alternate architecture for small satellites brings a whole new paradigm. The small modular satellites can be assembled and reassembled into various configurations best suited for the task at hand or be used to dispose space debris. Notably, with this modular small-satellite approach, the modules can be launched in rapid response for low cost to counter losses, aggregate into larger satellites with the latest sensor, propulsion and communications technology and add increased flexibility for planetary missions.

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FEMTOSATS FOR EXPLORING PERMANENTLY SHADOWED REGIONS ON THE MOON

Alvaro Diaz-Flores,[*] Jorge Martinez-Dominguez,[†] Leonard Dean Vance,[‡] Himangshu Kalita,[§] Jekan Thangavelautham,[**] and Team LASER[††]

In this paper, we explore the utility of FemtoSats to perform preliminary exploration and mapping of the Lunar Permanently Shadowed Regions (PSRs) as part of NASA BIG 2020 Competition. FemtoSats are spacecraft architectures that are less 100 grams or less. In particular, we focus on the launching of the FemtoSat for the first time and determine way for a lander to determine the direction, location, linear and angular velocity. We compare two approaches, launching of FemtoSats individually and using a rocket-propelled carrier vehicle. These are high-risk, high reward missions where losing one FemtoSat does not mean the mission is in danger as it happens with regular satellite missions. The exact depths of these PSRs are not exactly known. Sending FemtoSats into these terrains makes for a viable mission to map the surface. The FemtoSats would be launched from a lander and lit up using LED lights. Their trajectory tracked until falling into the PSRs and landing on the surface. The trajectory and landing location could be used to determine the depth of the craters and obtain temperatures readings upon contact. Sending a series of these FemtoSats, it is possible to map the topology of a crater region. If the FemtoSats remain tracked once on the PSR surface, a laser system onboard the lander can be pointed at the FemtoSat and used to power it over hours, days and weeks. The work developed here consists of making a generic conceptual design for FemtoSats and apply it to the exploration of the PSR's. The Lunar PSR has remained dark for millions of years. The temperatures are well below –150 °C, and it is unclear if water-ice is at the surface or below surface regolith. Using this approach of laser power beaming to the FemtoSat, we hope to keep it alive under extreme conditions and prolong operations in the PSR.

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AAS 21-449

MAXIMIZING DUST DEVIL FOLLOW-UP OBSERVATIONS ON MARS USING CUBESATS AND ON-BOARD SCHEDULING

Robyn Woollands,[*] [†] Federico Rossi,[‡] Tiago Stegun Vaquero,[§] Marc Sanchez Net,[**] S. Sandra Bae,[††] [‡‡] Valentin Bickel,[§§] and Joshua Vander Hook[***]

Several million dust devil events occur on Mars every day. These events last, on average, about 30 minutes and range in size from meters to hundreds of meters in diameter. Designing low-cost missions that will improve our knowledge of dust devil formation and evolution, and their connection to atmospheric dynamics and the dust cycle, is fundamental to informing future crewed Mars lander missions about surface conditions. In this paper we present a mission for a constellation of low orbiting Mars cubesats, each carrying imagers with agile pointing capabilities. The goal is to maximize the number of dust devil follow-up observations through real-time, on-board scheduling. We study scenarios where cubesats are equipped with a 2.5 degree boresight angle camera that accommodates five slew positions (including nadir). We assume a concept of operations where the cubesats autonomously survey the surface of Mars and can autonomously detect dust devils from their surface imagery. When a dust devil is detected, the constellation is autonomously re-tasked through an on-board distributed scheduler to capture as many follow-on images of the event as possible, so as to study its evolution. The cubesat orbits are propagated assuming two-body dynamics and the ground tracks and camera field of view are computed assuming a spherical Mars. Realistic inter-agent communication link opportunities are computed and included in our optimization, which allow for real-time event detection information to be shared within the constellation. We compare against a powerful "omniscient" oracle which has a priori knowledge of all dust devil activity to show the gap between predicted performance and the best possible outcome. In particular, we show that the communications are especially important for acquiring follow-up observations, and that a realistic distributed scheduling mechanism is able to capture a large fraction of all dust devil observations that are possible for a given orbit configuration, significantly outperforming a nadir-pointing heuristic.

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MULTI OBJECT TRACKING

Session Chair:

Session 30: Richard Linares, Massachusetts Institute of Technology

AAS 21-228

AUTONOMOUS SPACECRAFT TASKING USING MONTE CARLO TREE SEARCH METHODS

Adam Herrmann* **and Hanspeter Schaub†**

This work explores the use of Monte Carlo tree search (MCTS) and state-action value network regression to solve the single-spacecraft, multi-ground station Earth-observing satellite scheduling problem. Both algorithms are explored for their potential use as ground-based and on-board planning tools. An in-depth hyperparameter search is conducted for Monte Carlo tree search on the basis of performance, safety, and downlink opportunity utilization. A hyperparameter search is also conducted on the neural network architectures, and the general behavior of each network is explored to determine and validate learned behavior. Furthermore, each algorithm is compared to a genetic algorithm to determine the optimality gap and compare and contrast the use of reinforcement learning algorithms to classical optimization techniques. MCTS is shown to compute near-optimal solutions in comparison to the genetic algorithm. Furthermore, the state-action value networks are shown to match or exceed the performance of MCTS in five orders of magnitude less execution time, showing promise for execution on-board spacecraft.

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AAS 21-236

SPACE OBJECT TRACKING AT THE PURDUE OPTICAL GROUND STATION

Patrick Kelly[*] and Carolin Frueh[†]

The resident space object population in the near-Earth vicinity has steadily increased since the dawn of the space age. The resultant congestion in near-Earth space necessitates the availability of more complete and more accurate satellite tracking information to ensure the continued sustainable use of this environment. This paper outlines the development of the observation processing, astrometric solution, and orbit determination for the delivery of accurate satellite tracking information by means of optical observation conducted at the Purdue Optical Ground Station (POGS). The capability of this system is demonstrated using observations of the Wide Area Augmentation System (WASS) satellites.

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AAS 21-271

ORBIT DETERMINATION USING THE PROBABILITY HYPOTHESIS DENSITY FILTER AND ALTERNATE EQUINOCTIAL ORBITAL ELEMENTS*

James D. Brouk† and Kyle J. DeMars‡

Accurate and efficient orbit determination is imperative to effective utilization of the near-Earth environment. This paper formulates the Gaussian mixture probability hypothesis density (GM-PHD) filter using alternate equinoctial orbital elements (AEOEs) and the unscented transform. The GM-PHD filter, born of random finite sets and finite set statistics, allows greater flexibility than the extended Kalman filter. AEOEs are a set of coordinates strategically chosen to produce an efficient parameterization for orbit propagation. The proposed filter is tested through Monte Carlo simulation and analysis, examining the effects of reduced inter-object spacing and the number of data arcs on filter performance in comparison to a GM-PHD filter formulated in Cartesian coordinates using a linearization-based update.

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AAS 21-339

JOINT PROBABILISTIC DATA ASSOCIATION FILTER USING ALTERNATE EQUINOCTIAL ORBITAL ELEMENTS[*]

J. Cameron Helmuth[†] and Kyle J. DeMars[‡]

Space surveillance is a challenging problem, which grows more difficult with each new object in orbit. Loss of satellite custody can lead to dangerous consequences, such as collisions that result in the destruction of valuable resources and a dramatic increase in debris. A common approach to space object tracking is the joint probabilistic data association (JPDA) filter, which is a useful tool when measurement association is uncertain. Another piece of space surveillance involves propagating uncertainties in time. Given the tremendous number of objects in orbit and relatively infrequent measurements, this is a nontrivial problem. By parameterizing object states with alternate equinoctial orbital elements (AEOEs), improvements can be made in both computer time and accuracy as compared to using Cartesian coordinates. This paper merges JPDA with AEOEs to create an improved framework for space object tracking and compares the approach to a JPDA filter with Cartesian coordinates in numerical experiments.

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AAS 21-364

AUTONOMOUS SATELLITE DETECTION AND TRACKING USING OPTICAL FLOW

David Zuehlke,[*] Daniel Posada,[†] Madhur Tiwari,[‡] and Troy Henderson[§]

In this paper, an autonomous method of satellite detection and tracking in images is implemented using optical flow. Optical flow is used to estimate the image velocities of detected objects in a series of space images. Given that most objects in an image will be stars, the overall image velocity from star motion is used to estimate the image frame-to-frame motion. Objects seen to be moving with velocity profiles distinct from the overall image velocity are then classified as potential resident space objects. The detection algorithm is exercised using both simulated star images and ground-based imagery of satellites. Finally, this algorithm will be tested and compared using a commercial and an open-source software approach to provide the reader two different options based on their need.

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APPLICATIONS OF A MCMC SAMPLING AND CLUSTERING METHODS BASED RANDOMIZED-FINITE SET STATISTICS TECHNIQUE (R-FISST II)

U. R. Mishra,[*] W. R. Faber,[†] S. Chakravorty,[‡] and I. I. Hussein[§]

This paper presents a novel approach to keeping the Random Finite Set (RFS) based Bayesian recursions tractable. A randomized scheme using a Metropolis-Hastings, Markov Chain Monte Carlo (MCMC), based technique and Finite Set Statistics (FISST), termed Randomized FISST II (R-FISST II) is proposed. This technique samples highly probable target-observation association hypotheses and uses them to approximate the posterior RFS based multi-object Probability Density Function (PDF). It samples hypotheses without enforcing a heuristic number of samples so the number of samples is able to adjust naturally to the ambiguity of the Data Association Problem (DAP). Techniques of clustering of similar samples in hypotheses space are also presented. These details provide the technique with a level of robustness to false associations. Finally, we demonstrate the performances of this tracker for a multiple space object tracking problem with heavy clutter.

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