ASTRODYNAMICS 2021

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Front Cover Image:

This illustration shows NASA's Mars 2020 spacecraft, launched July 30, 2020, carrying the Perseverance rover as it approaches Mars. It landed safely on Mars on February 18, 2021.

Solar panels powering the spacecraft are visible on the cruise state at the top. The cruise stage is attached to the aeroshell, which encloses the rover and descent stage.

Entry, Descent, and Landing, or "EDL," begins when the aeroshell reaches the top of the Martian atmosphere, travelling nearly 12,500 mph (20,000 kph). It ends about seven minutes later, with Perseverance stationary on the Martian surface.

NASA's Jet Propulsion Laboratory in Southern California built and will manage operations of the Mars 2020 Perseverance rover for NASA. Credit: NASA/JPL-Caltech.

ASTRODYNAMICS 2021

Volume 177

ADVANCES IN THE ASTRONAUTICAL SCIENCES

Edited by
Paul F. Thompson
Craig A. McLaughlin
Diane C. Davis
Marcus J. Holzinger

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FOREWORD

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

Astrodynamics 2021, Volume 177, Advances in the Astronautical Sciences, consists of four parts totaling about 4,000 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 ASTRODYNAMICS VOLUMES

Astrodynamics 2021 appears as Volume 177, *Advances in the Astronautical Sciences*. This publication presents the complete proceedings of the AAS/AIAA Astrodynamics Specialist Conference 2021.

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Robert H. Jacobs, Series Editor

PREFACE

The 2021 AAS/AIAA Astrodynamics Specialist Conference, originally scheduled to take place in Big Sky, Montana, was held as a fully virtual event August 9-11, 2021. The meeting was hosted by the American Astronautical Society (AAS) Space Flight Mechanics Committee and co-hosted by the American Institute of Aeronautics and Astronautics (AIAA) Astrodynamics Technical Committee. Approximately 318 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 232 technical papers presented in 30 sessions on topics related to space-flight mechanics and astrodynamics. Dr. Maruthi Akella, Ashley H. Priddy Centennial Professor at the Department of Aerospace Engineering and Engineering Mechanics, The University of Texas at Austin, delivered the Brouwer lecture titled: "Mechanics Inspirations for Learning and Control."

The editors extend their gratitude to the Session Chairs and co-Chairs who made this meeting successful: Ossama Abdelkhalik, Davide Amato, Nicola Baresi, Spencer Boone, Natasha Bosanac, Angela Bowes, Anirudh Chhabra, Atri Dutta, Roshan Thomas Eapen, Damien Gueho, Brian Gunter, Casey Heidrich, Siamak Hesar, Jennifer Hudson, Isabelle Jean, Brandon Jones, John Kidd, Donghoon Kim, Gerhard Kruizinga, Alinda Mashiku, Piyush Mehta, Robert Melton, Anivid Pedros Faura, Christopher Roscoe, Ari Rubinsztejn, Jill Seubert, Puneet Singla, Rohan Sood, Powtawche Valerino, Jacopo Villa, and Xiangyuan Zeng,

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SPECIAL SESSION: MARS 2020

Session Chairs:

Session 1: Gerhard Kruizinga, NASA / Caltech JPL

Session 6: Paul Thompson, Jet Propulsion Laboratory

AAS 21-503

ORBIT DETERMINATION FOR THE MARS 2020 MISSION*

Jill Seubert,† Eric Gustafson,‡ Mark Jesick,§ Julie Kangas,**
Gerhard Kruizinga,†† Tomas Martin-Mur,‡‡ Sarah Elizabeth McCandless,‡
Tim McElrath,§§ Neil Mottinger,‡ Mark Ryne,‡ Sean Wagner,*** Mau Wong†††

NASA's Mars 2020 Mission successfully executed its Martian entry, descent, and landing sequence on February 18, 2021. Spacecraft navigation guided the spacecraft from its launch injection to entry into the Martian atmosphere; to do so, three trajectory correction maneuvers and two onboard state updates were performed. Navigation was required to provide an entry state with a maximum uncertainty of 2.8 km in position and 2.0 m/sec in velocity (3-σ); the flight performance was approximately 900 m and 66 cm/sec (3-σ). This paper presents the orbit determination models, measurements, filter strategies and performance throughout launch, cruise and Mars approach.

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ON-ORBIT CONTINGENCY PLAN FOR THE MARS 2020 MISSION[*]

Sarah Elizabeth McCandless,[†] Mark Jesick,[‡] and Gerhard Kruizinga[§]

NASA's Mars 2020 mission successfully launched to Mars July 30, 2020. An on-orbit contingency plan was developed to accomplish a controlled re-entry of the spacecraft in the event of a launch vehicle anomaly. The entire launch period was assessed, and satisfactory de-orbit burns were designed for every launch opportunity. An operational implementation was created for rapid adoption if needed, and validated using information from the Gravity Recovery and Climate Experiment (GRACE) satellites. This paper presents the orbit determination models and filter strategies used to conduct the pre-launch analyses, as well as the operational implementation validation methodologies and results.

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AAS 21-505

MARS 2020 NAVIGATION PERFORMANCE*

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On 30 July 2020 the Mars 2020 Perseverance rover was launched and then landed successfully 18 February 2021 in Jezero Crater. The Mars 2020 spacecraft required the same high-accuracy navigation performance as the Mars Science Laboratory (MSL), which landed on 05 August 2012. Like MSL, the key navigation requirements were driven by Entry, Descent and Landing atmospheric entry conditions, planetary protection and available propellant for trajectory correction maneuvers. This paper describes the pre-launch navigation analysis to satisfy the Mars 2020 navigation requirements and the actual navigation performance during cruise from launch to landing.

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MARS 2020 RADIOMETRIC DATA AND TELEMETRY PROCESSING, ATTITUDE ESTIMATION, AND THRUSTER CALIBRATION FOR ORBIT DETERMINATION*

Eric D. Gustafson,† Tomas J. Martin-Mur,‡ Gerhard L. Kruizinga,§ and Jill M. Seubert**

The Mars 2020 spacecraft was spin-stabilized during cruise, just like its predecessor, the Mars Science Laboratory. This spinning motion imparts a signature in the radiometric tracking data that must be dealt with in order to properly model the motion of the spacecraft's center of mass. We discuss how the Orbit Determination team pre-processed the data for efficient computations while also providing other benefits such as high-fidelity attitude modeling and on-board clock verification. Finally, we discuss the analysis and results of the in-flight thruster calibration activity.

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ENTRY, DESCENT, AND LANDING COMMUNICATIONS FOR THE MARS 2020 LANDER MISSION

Julie Kangas,[*] Sean Wagner,[†] Stuart Demcak,[‡] Chloe Sackier,[§] and Fernando Abilleira[**]

The Mars 2020 mission was launched on July 30, 2020 and successfully landed in Jezero Crater on February 18, 2021. The challenging Entry, Descent, and Landing (EDL) sequence was observed by ground stations on Earth and by orbiters at Mars. This paper discusses the design of the launch and arrival period to ensure maximum Earth visibility, the details of phasing the orbiting assets, and the development of the entry relay targets needed to ensure robust spacecraft telecommunications during EDL.

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AAS 21-509

MARS 2020 TRAJECTORY CORRECTION MANEUVER DESIGN[*]

Mark Jesick,[†] Mau Wong,[‡] Sean Wagner,[§] Julie Kangas,[**] and Gerhard Kruizinga[††]

The Mars 2020 mission launched on 30 July 2020 and arrived at Mars on 18 February 2021. Delivering the mission's Perseverance rover to Jezero Crater required adjusting the post-launch trajectory to remove the launch injection bias and to target the atmospheric entry conditions, while also satisfying requirements on the propellant usage and non-nominal impact probability at Mars. The Mars 2020 maneuver design team achieved these goals by designing and executing three propulsive maneuvers in flight. The accurate on-board execution of those maneuvers delivered the spacecraft into the Martian atmosphere in a state that allowed for a successful entry, descent, and landing on the surface. This paper details the maneuver design process and describes the design and execution of the three in-flight propulsive maneuvers.

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AAS 21-510

MANEUVER DESIGN IMPLEMENTATION AND VERIFICATION FOR THE MARS 2020 MISSION[*]

Sean Wagner,[†] Mau Wong,[‡] Christopher Pong,[§] Mark Jesick,[**] Julie Kangas,[††] and Gerhard Kruizinga[‡‡]

On February 18, 2021, the Perseverance rover landed in Jezero Crater on Mars, transported by the Mars 2020 spacecraft on a nearly seven-month journey to the Red Planet. The execution of three propulsive maneuvers during the interplanetary cruise phase was required to remove the launch-injection bias and deliver the spacecraft to the Mars atmospheric entry point. This paper focuses on the maneuver implementation and verification process between the navigation and spacecraft teams. Additionally, this paper discusses the execution error models that were used to determine maneuver performance and delivery accuracy at the atmospheric entry interface point.

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AAS 21-518

MARS 2020 PERSEVERANCE TRAJECTORY RECONSTRUCTION AND PERFORMANCE FROM LAUNCH THROUGH LANDING

Fernando Abilleira,[*] Gerard Kruizinga,[†] Seth Aaron,[‡] Kris Angkasa,[§] Todd Barber,[**] Paul Brugarolas,[††] Dan Burkhart,[‡‡] Al Chen,[§§] Stuart Demcak,[***] John Essmiller,[†††] John Gilbert,[‡‡‡] Eric Gustafson,[§§§] Julie Kangas,[****] Mark Jesick,[††††] Sarah Elizabeth McCandless,[‡‡‡‡] Swati Mohan, Neil Mottinger,[§§§§] Clara O'Farrell,[*****] Richard Otero,[†††††] Christopher Pong,[‡‡‡‡‡] Mark Ryne,[§§§§§] Jill Seubert,[******] Paul Thompson,[††††††] Sean Wagner,[‡‡‡‡‡‡] and Mau Wong[§§§§§§]

The Mars 2020 (M2020) Mission carrying Perseverance, the most advanced rover ever sent to Mars, successfully launched on an Atlas V 541 (AV-088) launch vehicle from the Eastern Test Range (ETR) at Cape Canaveral Air Force Station (CCAFS) in Florida at 11:50:00 UTC (T-Zero time) on July 30, 2020. After some station reconfiguration, carrier/telemetry were locked at both Deep Space Network (DSN) Canberra and Goldstone stations. Perseverance entered the Martian atmosphere at 20:36:50 Spacecraft Event Time (SCET) UTC, and landed inside Jezero Crater at 20:43:49 SCET UTC on February 18, 2021. Confirmation of nominal landing was received at the DSN Goldstone and Madrid tracking stations via the Mars Reconnaissance Orbiter at 20:55:11 Earth Received Time (ERT) UTC. This paper summarizes in detail the actual vs. predicted performance in terms of launch vehicle events, launch vehicle injection performance, actual DSN spacecraft lockup, trajectory correction maneuver performance, Entry, Descent, and Landing events, and overall trajectory and geometric characteristics.

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AAS 21-523

MARS RECONNAISSANCE ORBITER NAVIGATION STRATEGY FOR SUPPORT OF MARS 2020 MISSION'S ENTRY, DESCENT AND LANDING SEQUENCE[*]

Premkumar R. Menon,[†] Sean V. Wagner,[‡] David C. Jefferson,[§] Eric J. Graat,[**] Kyong J. Lee,[**] and Robyn M. Woollands[††]

The Mars Reconnaissance Orbiter provided primary relay support during the Mars 2020 mission's entry, descent, and landing sequence on February 18, 2021. To position the orbiter for relay support during this sequence, two propulsive maneuvers were performed: the first on September 2, 2020 and the second on January 20, 2021. This paper documents the maneuver strategy developed by the navigation team for positioning the Mars Reconnaissance Orbiter to within phasing requirements to support the Mars 2020 mission during landing and provides details on how well those phasing requirements were met.

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PLANETARY PROTECTION REQUIREMENTS AND AIMPOINT BIASING FOR MARS 2020 MISSION[*]

Mau Wong,[†] Julie Kangas,[‡] Mark Jesick,[§] Sean Wagner,[**] and Gerhard Kruizinga[††]

The Mars 2020 mission was launched from Cape Canaveral, Florida on July 30, 2020, and landed at Mars Jezero Crater on February 18, 2021. Throughout the 7-month interplanetary trajectory, there were various requirements and constraints the navigation team had to observe. Particularly pertinent to trajectory control and maneuver design were the planetary protection requirements for preventing microbial contamination of Mars. Consequently, the aimpoints for injection and early TCMs were biased away to reduce the probability of unintended Mars impact, thus satisfying these requirements. In addition, extensive pre-launch analyses were done to ensure other requirements could be met with high probabilities.

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THE MARS 2020 PERSEVERANCE NAVIGATION FILTER[*]

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The Mars 2020 (M2020) Entry Descent and Landing (EDL) system delivered a rover named “Perseverance” at Jezero crater (Mars) on February 18th, 2021. M2020 EDL used a Guidance Navigation and Control (GN&C) system to achieve its landing target objectives. The navigation filter (NavFilter) integrated Descent Inertial Measurement Unit (DIMU) measurements to estimate position and attitude. The NavFilter also used the Terminal Descent Sensor (TDS) to estimate surface-relative position and velocity corrections. The NavFilter provided all of the dynamic state information to the entry controller, entry guidance, Lander Vision System (LVS) and powered descent guidance and control algorithms. The NavFilter for Perseverance is based on Curiosity’s NavFilter with a couple of modifications.

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ASSESSMENT OF M2020 TERRAIN RELATIVE LANDING ACCURACY: FLIGHT PERFORMANCE VS. PREDICTS[*]

Swati Mohan,[†] Andrew E. Johnson,[‡] Paul Brugarolas,[§] Yang Cheng,[**] Richard Otero,[††] Nikolas Trawny,[‡‡] Seth Aaron,[§§] Fred Serricchio,[***] James Montgomery,[†††] Jordi Casoliva,[‡‡‡] and Allen Chen[§§§]

Terrain Relative Navigation (TRN) was a critical enabling Entry, Descent, and Landing (EDL) technology that enabled Mars 2020 mission Perseverance rover to land at Jezero crater. TRN provides real-time, autonomous, map-relative position determination and generates a landing target based on a priori knowledge of hazards. The required performance for TRN was to land within 60m of the selected target. The required 60m was sub-allocated to various error sources in three major categories: targeting error, knowledge error, and control error. The targeting error is the error in selecting an appropriate landing target and the knowledge of the target on the surface. It includes the Lander Vision System (LVS) position localization with respect to the ground, the synchronization between the Lander Vision System measurement and the main Navigation filter, and errors associated with the LVS Reference Map and Safe Target Selection (STS). The knowledge error is the contribution of knowledge growth from the synchronization with LVS to touchdown. The control error encompasses how accurately the system could stay on the desired reference trajectory. The TRN error budget uses a combination of analysis, simula-

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tion, and hardware testing results to bound the various error contributions obtained during the verification and validation process. This paper first presents a description of the TRN system, focusing on the architecture of LVS and STS. The paper then gives a detailed overview of the TRN error budget, with a description of the major error contributions in each of the three categories. Next, the paper gives the results for three versions of the error budget, pre-launch, inflight pre-landing, and post-landing. The paper compares the pre-flight analysis, the pre-landing analysis using in-flight data during cruise, to the post-landing analysis of the TRN performance. Pre-landing analysis best estimate of the landing performance was 33m, compared to the 60m requirement. Post-landing analysis estimated a landing accuracy of 8.53m or better, much better than the 33m pre-landing estimate. The actual post-landing imagery calculated the distance of the rover to the targeted location to be 5m. The post-landing analysis closely bounds the image-based assessment of landing accuracy, indicating the success of the error budget architecture in bounding the landing accuracy, as well as the fidelity of the simulations used to model and predict performance.

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MARS RECONNAISSANCE ORBITER MANEUVER PLAN FOLLOWING MARS 2020 LANDING[*]

Sean V. Wagner[†] and Premkumar R. Menon[‡]

The Mars Reconnaissance Orbiter spacecraft continues to perform valuable science observations at Mars, provide telecommunication relay for surface assets, and characterize landing sites for future missions. The spacecraft provided the primary relay support for the Mars 2020 mission during entry, descent, and landing on February 18, 2021. This paper discusses the propulsive maneuver plan following the Mars 2020 landing to return the spacecraft to its primary science orbit by November 2021 and maintain it through 2029. Alternate maneuver plans considered for supporting Mars 2020 surface operations and the entry, descent, and landing of the ExoMars 2022 mission are also described.

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ANALYSIS OF MARS 2020 PERSEVERANCE ENTRY, DESCENT, AND LANDING ATTITUDE INITIALIZATION PERFORMANCE

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The Mars 2020 Perseverance rover successfully landed at Jezero Crater on February 18, 2021. To perform this feat, the entry, descent, and landing navigation filter must be initialized with an estimate of the spacecraft state, which includes attitude from the cruise attitude control subsystem. Accuracy of this initial attitude estimate has an impact on important metrics such as touchdown velocity. This paper presents a post-landing reconstruction of the attitude initialization error budget, showing that the requirement of 0.15 deg (3σ, per axis) was met. Each error source is described and analyzed, including flight telemetry where possible. Analysis of the error budget shows that it is driven by systematic sun sensor errors, star-scanner-to-sun-sensor alignment stability, and inertial-measurement-unit-to-sun-sensor alignment stability. Finally, a contingency plan to initialize the navigation filter in the event of a star scanner failure is presented. While this plan was not needed in flight, results indicate that the attitude initialization requirement could have still been met in this off-nominal scenario.

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AAS 21-569

MARS 2020 PERSEVERANCE ENTRY DESCENT AND LANDING SIMULATION STATISTICAL ANALYSIS AND OPERATIONS[*]

P. Daniel Burkhart,[†] Seth Aaron,[‡] and Clara O'Farrell[§]

On February 18, 2021, the Perseverance rover and Ingenuity helicopter demonstration landed at Jezero Crater. The Entry, Descent, and Landing (EDL) architecture, largely the same used to land Curiosity at Gale Crater on August 6, 2012, required high-fidelity flight dynamics simulation with two independent tools to verify performance. The process for creating the EDL simulation using the Dynamics Simulator for Entry, Descent and Surface landing (DSENDS) tool will be discussed, along with its use for independent verification of the EDL statistical analysis results and reference trajectory simulation. Analysis and usage details both in development and cruise, along with post-landing assessment of the prediction performance of the simulation, will also be discussed.

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RECONSTRUCTED FLIGHT PERFORMANCE OF THE POWERED DESCENT GUIDANCE AND CONTROL SYSTEM FOR THE MARS 2020 PERSEVERANCE MISSION[*]

Jordi Casoliva,[†] Gurkirpal Singh,[†] Paul Brugarolas,[‡] and David W. Way[§]

On February 18th, 2021, the Mars 2020 mission successfully landed the "Perseverance" rover at Jezero crater on Mars. The Powered Descent Guidance and Control (PDGC) system was inherited from the Mars Science Laboratory mission and its parameters were tuned to support Terrain Relative Navigation for the Mars 2020 mission. The PDGC system architecture consists of a trajectory and an attitude commander, six feedback control loops and thruster allocation logic. The PDGC commands eight throttleable Mars Lander Engines to actively guide and control the vehicle during each powered flight phase. This paper describes the design and the as-flown performance of the PDGC system.

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AAS 21-599

MARS 2020 PERSEVERANCE EDL GNC SAFE TARGET SELECTION RECONSTRUCTION[*]

Paul Brugarolas,[†] Jordi Casoliva,[‡] David W. Way,[§] and Soumyo Dutta[**]

On February 18th, 2021, NASA landed Perseverance on the Jezero crater (on Mars) using a new Terrain Relative Navigation (TRN) capability. TRN is comprised of a new sensor, the Lander Vision System (LVS), and a new GNC algorithm, the Safe Target Selection (STS). LVS localized the descent vehicle with respect to a map. STS selected the safe landing target within a reachable region from the on-board Safe Targets Map (STM). The landing target was then handed to the Mars Science Laboratory (MSL) heritage powered descent GNC system to execute the landing. This paper describes the design and the as-flown performance of the STS algorithm.

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AAS 21-600

MARS 2020 PERSEVERANCE ENTRY DESCENT AND LANDING GUIDANCE NAVIGATION AND CONTROL

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On February 18th, 2021, NASA landed Perseverance on the Jezero crater (Mars). This paper presents an overview of the Guidance, Navigation and Control (GNC) system for the Entry, Descent, and Landing (EDL) phases of the Mars 2020 Mission. It describes the GNC architecture, including sensors, actuators and algorithms. It takes the perspective of the GNC mode commander and shows its as-flown performance.

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AAS 21-601

MARS 2020 PERSEVERANCE ENTRY CONTROLLER DESIGN AND FLIGHT RECONSTRUCTION

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On February 18th, 2021, NASA landed Perseverance on the Jezero crater (on Mars). An entry Guidance, Navigation, and Control (GNC) system delivered the vehicle to the desired landing ellipse. The navigation filter propagated position and attitude states initialized from cruise using Inertial Measurement Unit (IMU) measurements. The entry guidance modulated the lift vector through bank commands to reach the parachute deploy conditions. The entry controller commanded the propulsive Reaction Control System (RCS) to track the bank commands while doing rate damping on angle-of-attack and sideslip. This paper describes the design and the as-flown performance of the entry controller.

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AAS 21-679

MAVEN NAVIGATION SUPPORT OF THE MARS 2020 PERSEVERANCE ENTRY, DESCENT AND LANDING[*]

Stuart Demcak,[†] Robert Beswick,[‡] Eric Graat,[§] Rodica Ionasescu,[**] Brian Young,[††] Fernando Abilleira,[‡‡] and Julie Kangas[§§]

Through three years of maneuvering, the MAVEN orbiter was able to support the Mars 2020 (M2020) Perseverance Entry, Descent and Landing (EDL), while also changing to a more relay friendly orbit and preserving a mission lifetime through 2030. The synchronization of the MAVEN orbit for M2020 EDL will be reviewed, followed by a description of the MAVEN phasing for EDL. Potential concerns that arose from large density variations will be discussed, along with the interfaces between MAVEN and M2020.

[View Full Paper]

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DESIGNING OFF-NOMINAL OPERATIONS TESTS FOR CRITICAL EVENTS – MARS 2020 PERSEVERANCE

Scarlett E. Koller* and Dr. Julia Bell*

For the Mars 2020 Perseverance Mission, three off-nominal Operations Readiness Tests (ORTs) were carried out, with the goal of exercising the ability of the flight operations team to respond to unexpected in-flight anomalies. This is done by operating the Systems Testbed through a simulated Critical Event in real time, with simulated anomalies occurring during the Critical Event, and piping the data into Flight Operations venues as if the scenario were occurring in flight. The flight operations staff must then work through the events in real time using the real ground systems, including resolving anomalies in a flight-like manner during off-nominal tests.

As the units under test (UUTs) are the operations staff and entire ground system rather than the flight system itself, test development is a non-trivial undertaking. This paper gives a high-level explanation of the approach taken by the "Gremlin" team at JPL tasked with development of two of the three Off-nominal ORTs (Launch & EDL). The "Gremlin" team comprised Mission Systems Engineers, some Subsystem Engineers who were not UUTs, and Testbed Engineers to develop anomalies that remained strictly unknown to the flight operations and ground staff under test.

The explanation of the approach includes key considerations for future development of operations tests and differences in approach for tests carried out at different stages of the mission. The test development approaches were similar between the two ORTs described in this paper, with differences relating to the different Critical Events themselves and the experience level of the flight team at the different stages of the mission. Those differences are described in detail as part of considerations for future operations test development.

The paper includes descriptions of the anomaly selection process and what factors were accounted for in selection, the process of anomaly and resolution implementation in the testbed and the challenges associated with use of an imperfect ground-based testbed. The key points of note include the difficulty of crafting anomalies that were simultaneously plausible and feasible to implement in the testbed venue by engineers who were not experts in the behavior of the subsystems in question. (The relevant experts were nearly always UUTs and therefore unavailable for consultation.) A factor of note in anomaly selection was also the development of multiple solution pathways that would sufficiently exercise the operations team's ability to work interdependently with experts in different subsystems.

Key takeaways from this paper include not only the necessity of testing the human operations and ground systems for robustness in the face of mission anomalies, but also the complexity of developing a technically feasible test that will adequately exercise the team's ability to respond effectively to anomalies. Such tests have value not only for assessing readiness for Critical Events but as training for the operations team itself.

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LOW THRUST TRAJECTORIES

Session Chairs:

Session 2: Jennifer Hudson, Naval Postgraduate School

Session 24: Isabelle Jean, Canadian Space Agency

AAS 21-535

A ROBUST FINITE FOURIER SERIES APPROACH FOR LOW-THRUST EARTH-MOON TRAJECTORIES DESIGN

Madhusudan Vijayakumar* **and Ossama Abdelkhalik†**

This paper introduces a shape based Robust Finite Fourier Series (R-FFS) approach for the construction of 2D and 3D continuous low-thrust Earth-Moon trajectories. A constraint on the maximum thrust level is enforced and a restricted three-body dynamic framework is assumed. The trajectory is divided into three phases: escape, intermediate, and capture phases. The thrust-coast-thrust strategy is employed where the escape and capture phases are powered spirals and the intermediate phase is a coasting arc. The three body dynamics of the Earth-Moon system are leveraged to provide a zero-thrust plane change in the intermediate phase while maintaining the escape and capture phases each to be planar spirals. The proposed method is used to generate low-thrust trajectories that insert the spacecraft into Halo orbits. To the best of the authors' knowledge this is the first implementation for Finite Fourier Series shape based methods in generating transfers to Halo orbits. Another contribution of this paper is regarding the robustness of the R-FFS method. Specifically, a segmentation approach is developed in this paper for spiral trajectories that have large number of revolutions. This segmentation makes the R-FFS method more robust compared to the previous FFS method as detailed in the comparisons presented in this paper.

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PERIODIC ORBITS AS VIABLE LANDING SOLUTIONS WITH AN ABORT OPTION AT EUROPA

Luke Bury,[*] Jay McMahon,[†] and Martin W. Lo[‡]

Moons of the outer planets may offer some of the greatest scientific treasures in the solar system but they are exceedingly hard to reach, especially to land on. Great distances and complicated dynamical environments make this a difficult problem. Two capabilities that could help enable such a mission would be if the spacecraft could observe its target site prior to landing, and if it could abort the landing in the event of a problem and come back later. Each of these requirements relies on repeatability in the multi-body problem, which is non-trivial to achieve. In the current work, a new method for finding solutions with such repeatability is presented. Certain periodic orbits that tangentially intersect the surface of Europa and are themselves either stable or nearly-stable may be able to closely observe their target sites prior to landing and also act as their own abort solutions. 18 such periodic orbits, or "abort solutions," are identified.

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AAS 21-571

LOW-THRUST VENUS TRAJECTORIES AT LOW AND HIGH FIDELITY

Darcey R. Graham,[*] Jacob A. Englander,[†] Nicholas J. Rattenbury,[‡] and John E. Cater[§]

Interplanetary trajectory design is a challenge when considering small spacecraft with low-thrust systems. This work examines a potential Venus mission as a case study for a low-fidelity solution, which will then be used as an initial guess by a higher-fidelity optimizer. The low-fidelity solution uses a modified Sims-Flanagan transcription with n-body perturbations, with a global search performed using a monotonic basin hopping (MBH) algorithm. This allows a large problem space to be searched for preliminary design. Feasible solutions found can then be used as an initial guess by the higher-fidelity optimizer, which re-solves using an explicit integrator.

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AAS 21-577

ANALYSIS OF CISLUNAR TRANSFERS DEPARTING FROM A NEAR RECTILINEAR HALO ORBIT USING SOLAR ELECTRIC PROPULSION

Scott N. Karn,[*] Steven L. McCarty,[†] and Melissa L. McGuire[‡]

An analysis is completed to support the design of optimized trajectories of a massive spacecraft from an L2 Southern NRHO to a Distant Retrograde Orbit and a L2 Northern NRHO using a Solar Electric Propulsion System (SEP). An optimized trajectory is developed for each transfer for a 54 t spacecraft utilizing a 26.6 kW SEP system. A parameterization is developed for each reference transfer to allow analysis of the sensitivity of the trajectory to changes in vehicle mass, SEP power, and Ion Propulsion System (IPS) performance. Required Δv for each transfer is characterized by the initial acceleration of the spacecraft, thus allowing trajectories to be assessed over a wide range of vehicle mass and SEP power inputs. This approach is shown to be useful in identifying optimal IPS configurations for minimizing propellant requirements for the reference transfers. Additionally, the analysis identifies regions where increases in SEP power do not immediately result in a corresponding decrease in required propellant as well as highlights the relative sensitivities of propellant requirements to changes in IPS thrust and specific impulse.

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AAS 21-595

INTERPLANETARY LOW-THRUST TRAJECTORY DESIGN TO LIBRATION POINT ORBITS VIA SIMS-FLANAGAN TRANSCRIPTION

Yuri Shimane[*] and Koki Ho[†]

While low-thrust electric propulsion (EP) enables interplanetary missions to deliver larger payload fractions, the orbit insertion phase often necessitates a large, instantaneous ΔV maneuver, rendering it difficult to be conducted by an EP system alone. In contrast, missions to libration point orbits (LPO) may leverage ballistic capture strategies, resulting in no instantaneous ΔV maneuvers required. This work presents a modification to the Sims-Flanagan Transcription for interplanetary low-thrust trajectory design arriving at LPOs by incorporating flexible arrival into an insertion point on their stable manifolds.

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AAS 21-610

AUTONOMOUS GUIDANCE FOR CISLUNAR ORBIT TRANSFERS VIA REINFORCEMENT LEARNING

Lorenzo Federici,[*] Andrea Scorsoglio,[†] Alessandro Zavoli,[‡] and Roberto Furfaro[§]

This paper investigates the use of reinforcement learning for the optimal guidance of a spacecraft during a time-free low-thrust transfer between two libration point orbits in the cislunar environment. To this aim, a deep neural network is trained via Proximal Policy Optimization to map any spacecraft state to the optimal control action. A general-purpose reward is used to guide the network toward a fuel-optimal control law regardless of the specific orbits considered, and without the use of any ad-hoc reward shaping technique. Eventually, the learned control policies are compared with the optimal solutions provided by a direct method in two different mission scenarios, and Monte Carlo simulations are used to assess the policies robustness to navigation uncertainties.

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DEPARTURE AND TRAJECTORY DESIGN APPLICATIONS USING STRETCHING DIRECTIONS

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

Stable or nearly stable orbits do not always possess well-distinguished manifold structures that assist in departing from or arriving onto the orbit. Generally, for potential missions, the orbits of interest are nearly stable to reduce the possibility of rapid departure. The stable nature of these orbits also serves as a drawback for insertion or departure from the orbit. The Near Rectilinear Halo Orbits (NRHOs) and the Distant Retrograde Orbits (DROs) offer some potential long-horizon trajectories for exploration missions. The current investigation focuses on leveraging the stretching direction as a tool for departure and trajectory design applications. The magnitude of the state variations along the maximum stretching direction is expected to grow rapidly and, therefore, offers information for efficient departure from the orbit. Similarly, the maximum stretching in reverse time, enables arrival with a minimal maneuver magnitude.

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TOWARDS OPTIMAL LYAPUNOV CONTROLLERS FOR LOW-THRUST LUNAR TRANSFERS VIA REINFORCEMENT LEARNING

Harry Holt,[*] Nicola Baresi,[†] and Roberto Armellin[‡]

Future missions to the Moon and beyond are likely to involve low-thrust propulsion technologies due to their propellant efficiency. However, these still present a difficult trajectory design problem. Lyapunov control laws can generate suboptimal trajectories with minimal computational cost and are suitable for feasibility studies and as initial guesses for optimisation methods. In this work we combine Lyapunov control laws with state-dependent weights trained via reinforcement learning to design low-thrust transfers from GTO towards low-altitude Lunar orbits. The agent is able to explore third-body effects during training and learn to remain stable to perturbations during the different transfer phases. Three different approaches are investigated: backwards propagation, backwards propagation with freed geometry, and forwards propagation including rendezvous capability with the Lunar SOI. The last of these proves to be the most successful, coming within 6:6% of the optimal solution.

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AAS 21-664

FEASIBLE LOW-THRUST TRAJECTORY IDENTIFICATION VIA A DEEP NEURAL NETWORK CLASSIFIER

Ruida Xie* **and Andrew G. Dempster†**

In recent years, deep learning techniques have been introduced into the field of trajectory optimization to improve convergence and speed. Training such models requires large trajectory datasets. However, the convergence of low thrust (LT) optimizations is unpredictable before the optimization process ends. For randomly initialized low thrust transfer data generation, most of the computation power will be wasted on optimizing infeasible low thrust transfers, which leads to an inefficient data generation process. This work proposes a deep neural network (DNN) classifier to accurately identify feasible LT transfer prior to the optimization process. The DNN-classifier achieves an overall accuracy of 97.9%, which has the best performance among the tested algorithms. The accurate low-thrust trajectory feasibility identification can avoid optimization on undesired samples, so that the majority of the optimized samples are LT trajectories that converge. This technique enables efficient dataset generation for different mission scenarios with different spacecraft configurations.

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AAS 21-675

SURVEY OF LOW-ENERGY TRANSFERS TO LUNAR LIBRATION POINT ORBITS WITH TARGETED L_1 TRANSITS

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Low-energy transfers between the Earth and lunar libration point orbits involve transits through the L_1 and L_2 equilibrium points. The available transits through an exit are dictated by the escape dynamics and are sensitive to the initial conditions in the presence of fractal basin boundaries. By introducing a small maneuver along the stable manifolds of the destination orbits, trajectories initially bounded for L_2 are successfully diverted to exit via the L_1 gateway. The resulting transfers are optimized using evolutionary algorithms in the circular restricted three-body problem, yielding prospective transfers with a shorter time of flight.

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PSEUDOSPECTRAL CONVEX LOW-THRUST TRAJECTORY OPTIMIZATION IN A HIGH-FIDELITY MODEL

Christian Hofmann* and Francesco Topputo†

The low-thrust minimum-fuel trajectory optimization problem is solved in a high-fidelity model using convex optimization. The problem is convexified and discretized with the Radau pseudospectral method. We apply a homotopic approach and successively increase the complexity and accuracy of the model to enhance convergence properties. Solar radiation pressure, variable specific impulse and maximum thrust, and the perturbation of other bodies are considered. A homotopy from the minimum-energy to the minimum-fuel problem is added. The performance is assessed in minimum-fuel interplanetary transfers to two asteroids. Moreover, the developed approach is integrated into a closed-loop guidance simulation. The numerical simulations show that the sequential convex programming approach is able to solve highly nonlinear optimization problems to high accuracy with poor initial guesses.

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AAS 21-697

OVERVIEW OF THE LUNAR TRANSFER TRAJECTORY OF THE CO-MANIFESTED FIRST ELEMENTS OF NASA'S GATEWAY

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This paper documents the current design reference mission planned for the first two elements of NASA's Gateway. When launched together, the Power and Propulsion Element and Habitation and Logistics Outpost comprise the Co-Manifested Vehicle (CMV).[1] The low-thrust transfer between the initial parking orbit and the final insertion into the operational Near Rectilinear Halo Orbit is described. While each specific trajectory depends on launch date, trends are identified in the dynamics and orientation of the CMV as it traverses its spiral orbit. This paper describes the interplay between various assumptions and constraints on the development of the low thrust lunar transfer.

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AAS 21-704

DESIGN OF LOW-THRUST TRANSFERS FROM AN NRHO TO LOW LUNAR ORBITS: APPLICATIONS FOR SMALL SPACECRAFT

Beom Park,[*] Kathleen C. Howell,[†] and David C. Folta[‡]

With an expanding array of activities being examined in the vicinity of near rectilinear halo orbits (NRHOs), nearby destinations for small spacecraft are an essential component. Transfer trajectories from an NRHO to a low lunar orbit (LLO) is one such example, where the significant design challenges are associated with the low level of acceleration available to the spacecraft. A low-thrust trajectory design framework within the Earth-Moon Circular Restricted Three Body Problem is explored, utilizing a targeting problem comprised of two legs departing from the NRHO and arriving at an LLO. The performance of the devised framework is analyzed with multiple LLOs.

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AAS 21-705

LOW-THRUST DEPLOYMENT OF SATELLITE CONSTELLATIONS ABOUT MARS USING NONLINEAR ORBIT CONTROL

Mauro Pontani,* Marco Pustorino,† and Paolo Teofilatto‡

This research considers a Mars constellations composed of 12 satellites, devoted to telecommunications. While 3 satellites travel areostationary orbits, the remaining 9 satellites are placed in three distinct quasi-synchronous, inclined, circular orbits. The constellation at hand provides continuous global coverage, over the entire Mars surface. Orbit injection is accomplished using 4 carrier vehicles, which depart from a 4-sol orbit. Each carrier is driven toward the respective operational orbit using steerable and throttleable low-thrust propulsion, in conjunction with nonlinear orbit control. Lyapunov stability analysis leads to defining a feedback law that enjoys quasi-global stability properties. Orbit phasing concludes the constellation deployment, and is carried out by each satellite. The tradeoff between phasing time and propellant expenditure is characterized.

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AAS 21-721

EVALUATION OF LOW-THRUST SYNERGETIC MANEUVERS DURING PLANETARY FLYBYS

Ghanghoon Paik* **and Robert G. Melton†**

Previous interplanetary missions have used non-powered flyby maneuvers to gain delta-v via gravity assist. In this research, trajectories similar to previous missions are studied to compare the effect of applied continuous thrust while a spacecraft is flying inside a planet's sphere of influence. Compared to a free flyby, a spacecraft with continuous thrust capability can optimize the path and possibly allow a wider window for mission design. The focus is a proof-of-concept for gravity assists using continuous thrust within the SOI of each encountered planet for a synergetic Δv. With further development, it is expected to generate optimized trajectories to target a planet with powered gravity assist. In the interplanetary results, the algorithm was able to find a path with two successful powered planetary flybys from a given set of dates.

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AAS 21-771

SOLAR ELECTRIC PROPULSION MISSION DESIGN FOR SPACE TELESCOPE REFUELING AND SERVICING

Alex Pascarella,[*] Robyn Woollands,[†] and Siegfried Eggl[‡]

Space-borne observatories such as the James Webb Space Telescope (JWST) and the Nancy Grace Roman Space Telescope (RST), formerly WFIRST, are multibillion-dollar assets to be launched in 2021 and 2025, respectively. JWST is an infrared telescope with a 6.5-meter diameter primary mirror and RST is a near-infrared and visible telescope with a 2.4-meter primary mirror. Both telescopes are designed to operate in Halo orbits around the Sun-Earth second Lagrange point (SEL2). Five to ten years after launch, fuel for station keeping and attitude maneuvers will be depleted and the aforementioned assets will become essentially inoperable. Refueling and servicing missions to space telescopes could greatly enhance the science-per-dollar value and promote a more sustainable use of space facilities. In this paper, we present a low-thrust trajectory design for a refueling and servicing mission to JWST at SEL2. The problem is formulated using high-fidelity force and ephemeris models. Quasi-invariant manifolds are leveraged to reduce the fuel consumption required for sending a spacecraft from Earth orbit to rendezvous with JWST.

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CO-STATE INITIALIZATION WITH PARTICLE SWARM OPTIMIZATION FOR LOW-THRUST MINIMUM-FUEL TRAJECTORY OPTIMIZATION

Grant R. Hecht* and Eleonora M. Botta†

Mission design and optimization for spacecraft equipped with low-thrust propulsion is a complex problem. Among the proposed solutions, indirect methods apply calculus of variations and Pontryagin's maximum principle to analytically derive the necessary conditions for optimality, introducing additional co-state variables and formulating the problem as a two-point boundary-value problem (TPBVP). The solution of this TPBVP is the set of initial co-state conditions that result in the satisfaction of boundary conditions at the final time. These, when integrated in time together with initial conditions, result in the optimal trajectory. Shooting-based approaches may be used to solve the TPBVP, but typically do not guarantee convergence, which is highly dependent on the selection of the starting guess of co-state variables. In this paper, Particle Swarm Optimization (PSO) is proposed for initializing the co-state variables in low-thrust minimum-fuel trajectory optimization problems. PSO performs a global search of the solution space by attempting to minimize the weighted sum of squares of the TPBVP final boundary condition residuals for the minimum-energy problem, which is more easily solved compared to the minimum-fuel problem. Next, an energy-to-fuel homotopy is employed to iteratively solve the TPBVP for decreasing values of a perturbation parameter that allows gradually transitioning the minimum-energy trajectory to minimum-fuel. The proposed methodology is applied to a low-thrust transfer from a geostationary transfer orbit (GTO) to a L1 halo orbit in the Earth-Moon system. The resulting minimum-fuel trajectory is validated by comparison with publicly available solutions of the optimal low-thrust transfer for the GTO to L1 halo orbit transfer problem. Satisfactory performance in terms of convergence rate is obtained when large particle swarm sizes are employed. The proposed approach is of simple implementation and is applicable to a range of trajectory optimization problems, which is an advantageous feature for the preliminary phase of mission design.

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ASTEROIDS AND SMALL BODIES

Session Chair:

Session 3: Nicola Baresi, University of Surrey, United Kingdom

AAS 21-545

CLOSE PROXIMITY OPERATIONS AROUND ASTEROIDS USING AN IMPROVED SLIDING MODE APPROACH

Anivid Pedros Faura[*] and Jay W. McMahon[†]

Close-proximity operations around small bodies can be extremely challenging due to their highly uncertain dynamical environments. In this work, asteroid-hovering guidance law techniques are implemented and studied for a Bennu-like asteroid. First, a suitable controller for station keeping is presented by studying adaptive deadbands and changing control frequencies. Second, a modified sliding-mode control technique is used to transition from one hovering location to another while ensuring safety. A feasibility study is presented showing the limitations of the conventional multiple sliding mode controller.

[View Full Paper]

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AAS 21-573

DYNAMICAL EVOLUTION OF LANDERS IN THE FULL TWO-BODY PROBLEM OF BINARY ASTEROIDS

Tongge Wen*, and Xiangyuan Zeng†

This paper investigates the motion of a lander in a fully coupled spin-orbit binary system. The full dynamical equations are established, including the states of the lander and the two small celestial bodies. Both two primaries are represented by tetrahedral meshes when propagating their states. The mutual gravitational interactions between the two primaries and the attraction of the lander in this binary system are evaluated by the finite element method. The contact motion between the lander in arbitrary shapes/inertia and the asteroid surface is processed by the Polygonal Contact Model. The resulting framework is applied to the binary asteroid 1999 KW4. The effect of different internal structures of the second primary on the lander deployment is investigated. The dispersion of the final locations and the transfer time of the landing trajectories are summarized and compared, which can provide guidance for deploying a lander in binary systems.

[View Full Paper]

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AAS 21-617

CONSIDER COVARIANCE ANALYSES OF PERIODIC AND QUASI-PERIODIC ORBITS AROUND PHOBOS

Edoardo Ciccarelli[*] and Nicola Baresi[†]

The Martian Moons eXploration mission will be the first of its kind to sample and study Mars's moon Phobos for a prolonged period of time. The aim of this work is to show that the adoption of periodic and quasi-periodic retrograde trajectories would be beneficial for the scientific return of MMX. A consider covariance analysis is hereby implemented in order to compare the estimation of high-order gravitational field coefficients from different orbital geometries and processing different sets of observables. It is shown that low-altitude non-planar quasi-satellite orbits would refine the knowledge of the moon's gravity field.

[View Full Paper]

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AAS 21-626

ORBIT MAINTENANCE OF PERIODIC AND QUASI-PERIODIC ORBITS AROUND SMALL PLANETARY MOONS VIA CONVEX OPTIMIZATION

N. Bernardini,* N. Baresi,† and R. Armellin‡

Despite several missions, the origin of the two Martian moons, Phobos and Deimos, remains an open question. Martian Moons eXploration (MMX) is JAXA's next flagship mission and will explore the two Martian moons. The spacecraft will be placed in a quasi satellite orbit (QSO) around Phobos. Traditional methods for orbit maintenance around libration points are not applicable for these QSOs due to the rapid evolution of the orbit. In this paper we propose a new approach to perform the orbit maintenance on periodic and quasi-periodic orbits based on convex optimization. It is shown that using lossless and successive convexification, candidate MMX orbits can be maintained in the Hill problem of Phobos with 0.558 m/s.

[View Full Paper]

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AAS 21-644

APPLICATION OF A KINEMATIC IMPACT ON 99942 APOPHIS

Carly J. VeNard[*] and Davide Conte[†]

99942 Apophis, or simply Apophis, has been a near Earth asteroid of interest to the scientific community since its discovery in 2004. With a heliocentric orbit similar to that of Earth, the asteroid has several close encounters with our planet in the near future, specifically in 2029, 2036, and 2068. After 2068, the orbit of the asteroid is largely affected by the Yarkovsky effect, making it difficult to anticipate the propagation of its orbital position. This study utilizes the close Earth approach of Apophis in 2029 to perform a kinematic impactor maneuver onto the asteroid to deter its orbit from Earth, specifically during the 2036 close approach. This methodology uses a high-velocity projectile impact onto the asteroid to impart an artificial Δv to change the orbit of Apophis. This maneuver increases the close approach distance in 2036 by 24.6%, as well as tests the feasibility to perform deflection maneuvers on similar threats in the future.

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AAS 21-667

TRAJECTORY DESIGN AND ORBIT DETERMINATION OF HERA'S MILANI CUBESAT

C. Bottiglieri,* F. Piccolo,* A. Rizza,* C. Giordano,* M. Pugliatti,* V. Franzese,* F. Ferrari,* and F. Topputo*

Hera is the European contribution to the ESA-NASA collaboration AIDA. During the mission, two CubeSats will be released in proximity of the binary asteroid 65803-Didymos: Milani and Juventas. In this work, some challenging aspects of the mission analysis of Milani are presented. Original trajectory design solutions are devised as a response to demanding scientific and operational requirements in a low-gravity environment. Then, a navigation strategy based on a combination of radiometric and optical measurements is presented and results of the knowledge analysis are shown for the main phases of the mission.

[View Full Paper]

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AN ARCHITECTURE FOR AUTONOMOUS SMALL BODY EXPLORATION

D. J. Scheeres,* J. W. McMahon,† D. A. Baker,‡ D. H. Kuettel III,§ and S. Takahashi**

An integrated architecture for autonomous operations, including navigation and guidance, at small solar system bodies is presented. These results draw upon and integrate key results from a NASA ESI grant that has been active over the last few years. Our implementation of autonomous navigation, characterization and guidance techniques are built around fundamental dynamic operational modes that have been identified and implemented using ground-based navigation and exploration techniques in the small body environment. We consider these previous activities as having vetted a few common and effective approaches for small body navigation, which can be migrated into schemes that can be implemented autonomously.

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MULTIPLE OBSERVATION OPPORTUNITIES FOR TRANS-NEPTUNIAN OBJECTS PART 8

Allison Warren-Carroll, Anthony Kennedy, Jacob Stophel,[*] Sarah Wellence,[†] Samantha Ramsey,[‡] and James Evans Lyne[§]

This study is a continuation of previous efforts to identify trajectories to trans-Neptunian objects (TNO). The current work focuses on the use of delta-V Earth gravity assist maneuvers in combination with Jovian gravity assists to improve overall mission performance and launch characteristics. Launch is assumed to be accomplished using an Atlas V 551, and a HiPAT motor is used for deep space maneuvers. Missions to fourteen TNOs are presented, visiting a wide variety of object types including binaries, cubewanos, plutinos, a trinary system, and objects both with and without orbital resonance with Neptune. All fourteen missions are generally favorable in terms of C_3, transit time, arrival excess speed and achievable probe mass when compared to more direct mission architectures. Additionally, four targets are examined for the possibility of orbital capture. Overall, the missions presented in this study would allow scientists to observe materials present at the beginning of the formation of the solar system and result in an increased understanding of the Kuiper Belt.

[View Full Paper]

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AAS 21-785

GRAVITY ESTIMATION AT SMALL BODIES VIA OPTICAL TRACKING OF HOPPING ARTIFICIAL PROBES

Jacopo Villa,[*] Andrew French,[†] Jay McMahon,[‡] Daniel Scheeres,[§] and Benjamin Hockman[**]

Despite numerous successful missions to small celestial bodies, the gravity field of such targets has been poorly characterized so far. Gravity estimates can be used to infer the internal structure and composition of small bodies and, as such, have strong implications in the fields of planetary science, planetary defense, and in-situ resource utilization. Current gravimetry techniques at small bodies mostly rely on tracking the spacecraft orbital motion, where the gravity observability is low. To date, only lower-degree and order spherical harmonics of small-body gravity fields could be resolved. In this paper, we evaluate gravimetry performance for a novel mission architecture where artificial probes repeatedly hop across the surface of the small body and perform low-altitude, suborbital arcs. Such probes are tracked using optical measurements from the mothership's onboard camera and orbit determination is performed to estimate the probe trajectories, the small body's rotational kinematics, and the gravity field. The suborbital motion of the probes provides dense observations at low altitude, where the gravity signal is stronger. We assess the impact of observation parameters and mission duration on gravity observability. Results suggest that the gravitational spherical harmonics of a small body with the same mass as the asteroid Bennu, can be observed at least up to degree 40 within months of observations. Measurement precision and frequency are key to achieve high-performance gravimetry.

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SPACE SITUATIONAL AWARENESS

Session Chairs:

Session 5: Rohan Sood, The University of Alabama

Session 7: Brandon Jones, The University of Texas at Austin

The following paper listed in the program was not presented:

AAS 21-514

AAS 21-520

EVALUATION FRAMEWORK FOR CISLUNAR SPACE DOMAIN AWARENESS SYSTEMS

Simon Knister,[*] Benjamin R. Williams,[†] Dustin Hayhurst,[‡] Kirk W. Johnson,[§] and Bryan D. Little[**]

Evaluating cislunar Space Domain Awareness (SDA) architectures for future Space Traffic Management (STM) related functions requires developing performance and cost metrics that matter. Various detect and track metrics are proposed and are used to evaluate simple, geocentric, electro-optical, space-based architectures to determine the validity of the metrics and understand the performance versus cost trade-space. A model-based systems engineering (MBSE) approach is used to implement a reference scenario, understand cislunar physics, study scenario geometries, and compute metrics for multiple space-based architectures. Several simple sensing constellations are evaluated, and the results are compared. Ultimately, performance is largely affected by lunar exclusion angles for a target in a L_1 Lyapunov orbit and the most optimal architecture is determined to be a 4-ball, synodic LEO constellation.[1]

[View Full Paper]

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AAS 21-566

A PARALLEL NUMERICAL METHOD FOR THE FAST PROPAGATION AND ESTIMATION OF ORBITS

T. Feagin* and R. G. Gottlieb†

A very fast and accurate numerical method for the propagation and estimation of space trajectories is described. The method possesses several advantages over traditional methods especially when employed on parallel computing equipment. The method embodies a number of constituent techniques, including the Kustaanheimo-Stiefel transformation, a rapidly converging iteration, Gauss-Legendre quadrature methods of extremely high degree (which allow for the effective use of extremely large stepsizes), pseudo-evaluations, and a parallel gravitational model. The net result is a very fast and accurate parallel numerical method that is more than 50 times faster than the best of the commonly-used serial methods.

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AAS 21-603

EXCEEDANCE PROBABILITY FOR SHORT-TERM ENCOUNTERS

Ken Chan*

This paper discusses the "reasonableness" of the probability obtained for the collision of two orbiting objects which come into close proximity. The existing computation accuracy is not the issue. Of concern is the reliability of the input information. One method is to perform confidence analysis on the input parameters. Alternatively, a metric is formulated to gauge "the probability that this collision probability" will be exceeded. Such a probability is termed the "exceedance probability". Confidence limits and confidence intervals of the miss distance and the standard deviations, but not the cross section area radius, are obtained corresponding to specified ranges of the Exceedance Probability.

[View Full Paper]

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AAS 21-604

ELLIPTICAL HOVERING COLLISION PROBABILITY FOR LONG-TERM ENCOUNTERS

Ken Chan*

This paper is concerned with the analysis preceding the formulation of long-term collision probability of a secondary spacecraft hovering in an ellipse relative to a primary spacecraft. In the physical space, these elliptical orbits repeat themselves. However, if we have a time-dependent position covariance, we have to map these orbits into a common space of random variables so that we have a common basis for analysis. Two illustrative cases are analyzed. The first deals with minimal overlapping of the cycles mapped onto the space of random variables whereas the second deals with excessive overlapping. These two study cases illustrate that the concept of integrating the "flux" of time-dependent probability density functions leads to erroneous results because it yields collision probabilities greater than unity.

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AAS 21-622

OPTIMAL DESIGN AND VERIFICATION OF GRAVEYARD ORBITS FOR THE GALILEO CONSTELLATION

Félix Arribas de Antonio,* Roberto Armellin,† and David J. Gondelach‡

This paper presents two methods for the EoL disposal of spacecraft in Medium Earth Orbit (MEO) based on the efficient design of long-term stable graveyard orbits. The problem is first formulated as a multi-objective optimization one, where a bi-impulsive maneuver is optimized to dispose the spacecraft in a stable graveyard orbit for at least 100 years. The second method consists in a grid-search approach using "omega-targeting" maneuver based on the analysis of the conditions leading to stable graveyard orbits. In both methods a set of solutions are obtained seeking minimum fuel consumption and occurrence of conjunctions with operative spacecraft for at least 100 years. To reduce the computational time, spacecraft dynamics are simulated using semi-analytical orbit propagation techniques and a suitable dynamical model including the main geopotential terms, 3rd-body perturbations and solar radiation pressure. Finally, a phase space study is proposed to explain the key features of the disposal dynamics. We use satellites in the Galileo constellation as test cases.

[View Full Paper]

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EARLY INFORMATION PARAMETER-SET ANALYSIS FOR SATELLITE CLOSE APPROACHES USING MACHINE LEARNING

Brianna I. Robertson* and Alinda Mashiku†

Understanding orbital mechanics is essential in space flight and navigation applications, and leveraging modern force models for flight path projection remains an important aspect in space mission design and operation. However, force models do not capture all the dynamics or perturbations in the space environment and thus are subject to errors, called process noise, that grow over time. In mission operations for spacecraft, conjunction analysis and risk mitigation are important elements for safety of space operations and mission success. With recent advances in the field artificial intelligence, specifically in machine and deep learning algorithms, parameter-set analysis can be used to construct a model that provides early information for decision making and maneuver planning. In analyzing the relationship of several physics-based parameters, both independent and derived, from conjunction data messages (CDMs) and solar information, early information becomes viable in miss distance prediction with unsupervised learning techniques. The implementation of shallow binary classifiers and Long Short Term Memory (LSTM) recurrent neural networks help predict miss distance between primary and secondary objects within a given threshold, which is critical in observing high interest events (HIEs) with limited measurement updates.

Keywords - Orbital Mechanics, Collision Avoidance, Machine Learning, Unsupervised Learning, Long Short Term Memory

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AAS 21-657

PERFORMANCE ANALYSIS OF COVARIANCE BASED TRACK ASSOCIATION WITH MEAN MODIFIED EQUINOCTIAL ELEMENTS

Woosang Park[*] and Kyle T. Alfriend[†]

The performance of the Mahalanobis distance (MD) for the track association problem is analyzed by investigating the MD cumulative distribution function (MD-CDF). Numerical simulations are performed to examine how the dynamic nonlinearity of equations of orbital motion affects the MD-CDF in the long term propagation. The MD between the truth and estimated orbits is computed with states and covariance obtained by the recursive batch-least squares algorithm. 862 tracks are detected by 9 ground-based radars during the 12-hour orbit propagation of 100 space objects. The result showed that the mean-modified-equinoctial-based MD-CDF degrades slower than that of the Cartesian coordinate and osculating equinoctial elements.

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AAS 21-662

MODEL PREDICTIVE CONTROL AND SAFETY ANALYSIS FOR SATELLITE COLLISION AVOIDANCE

Axel Garcia,[*] Charles Dawson,[†] Miles Lifson,[‡] David Arnas,[§] Chuchu Fan,[**] Christopher Jewison,[††] and Richard Linares[‡‡]

The active LEO satellite population is expanding rapidly and is expected to grow by an order of magnitude over the decade. This growth necessitates both increased spacecraft control autonomy, and techniques to provide robust collision avoidance safety guarantees. These guarantees must take into account the interactions between multiple autonomous systems across heterogeneous populations under disaggregated operation and diverse control strategies. In this work, we develop linear and nonlinear model-predictive controllers for low-thrust optimal control for collision avoidance and proximity operations. Additionally, we provide controller-agnostic safety analysis based on control barrier functions to certify collision avoidance, even under unknown but bounded perturbations or adversarial disturbances. This approach is able to provide run-time safety guarantees, even for black-box controllers, as long as high-frequency, accurate ephemerides are provided for all relevant objects.

[View Full Paper]

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AAS 21-671

SINGLE-/MULTIPLE-REVOLUTION LAMBERT'S PROBLEM CONSTRAINTS FOR OPTICAL TRACK-TO-TRACK ASSOCIATION

Yang Yang,[*] Zhenwei Li,[†] Han Cai,[‡] and Yan Zhang[§]

In optical tracking scenarios for Resident Space Objects (RSOs), the observing arcs are usually sparse and short, resulting in failure of initial orbit determination using single tracks. Hence, track-to-track association (T2TA) for different time epochs is a prerequisite of refined orbit determination and follow-on catalogue maintenance of RSOs. In the previous work, the boundary value problem (BVP) optimization method and the BVP method with constraints (BVP-Con) of the single-revolution Lambert's problem have been proposed for T2TA. This work will consider multiple-revolution cases and establish a more general T2TA framework. The performance of the general BVP-Con method will be tested and validated by real-world optical data for RSOs in both geosynchronous Earth orbit and low Earth orbit collected by two all-sky electro-optical arrays at Changchun Observatory in China.

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AAS 21-684

PRELIMINARY DESIGN OF MULTI-CHASER ACTIVE DEBRIS REMOVAL MISSIONS WITH EVOLUTIONARY ALGORITHMS

Danilo Zona,* Lorenzo Federici,† and Alessandro Zavoli‡

This paper deals with the preliminary design of an active debris removal mission in Earth's orbit, where multiple active spacecraft are used to remove all the space debris belonging to a given cluster. The problem is posed as a purely combinatorial optimization problem and dealt with a Genetic Algorithm (GA). A novel permutation-based encoding, specifically designed to allow the simultaneous optimization of the sequence of targets, their distribution among the chaser spacecraft, and the selection of the best rendezvous epochs, is presented. Special permutation-preserving operators are introduced to improve the convergence capabilities of GA. Numerical results are presented for a case study involving a few dozens of debris and up to four chasers.

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AAS 21-717

ANALYSIS OF POTENTIAL COLLISION MANEUVER GUIDELINES FOR FUTURE SPACE TRAFFIC MANAGEMENT

Richard J. Macke,* Brian C. Gunter,† Mariel Borowitz,‡ and Megan Birch§

The growing requirement for a space traffic management system (STM) has prompted exploration of potential STM rules and regulations. To evaluate these proposals, a model must be developed that captures both the current behavior or resident space objects (RSOs) and their behavior under future STM guidelines. This paper discusses the development of such a model and simulation environment to examine proposed STM regimes by producing the impact on conjunctions between RSOs and the cost to satellite operators for each proposal. These are the costs and benefits that will be weighed when determining the effectiveness of each potential STM regime.

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AAS 21-729

ORBITAL CONGESTION ASSESSMENT BASED ON DIMENSIONALITY REDUCTION

Jorge Martinez,[*] Guillermo Escribano,[†] and Manuel Sanjurjo-Rivo[‡]

Many things have changed in the space industry since the early stages of the space era in the middle of last century, but laws and regulations have yet to catch up to technological advances. To help establishing appropriate space regulations, the current situation needs to be deeply analysed. The presented work tries to help in the specific field of space congestion, in which a thorough assessment in terms of collision risk is extremely complex. The objective is to develop an operational method to analyze big populations of catalogued objects in an all vs all manner, for assessing collision risk in the medium term, and facilitating a better Space Traffic Management. For that, we define and compute intermediate and semi-analytic metrics that help in establishing medium to long term collision trends from short-term simulations and yield results that are easy to present in a visual way. Results show how these metrics can help in establishing risk levels in the medium to long term in different orbital regimes.

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AAS 21-741

SENSOR TASKING FOR SPACE SITUATIONAL AWARENESS USING DEEP REINFORCEMENT LEARNING

Peng Mun Siew,* Daniel Jang,† and Richard Linares‡

Combinatorial complexity is a major obstacle to the sensor tasking problem for space situational awareness. Deep reinforcement learning has shown to be able to overcome the curse of dimensionality and has been successfully applied in this work. Several deep reinforcement learning agents are trained using proximal policy optimization and population-based training with an in-house developed SSA environment. The deep reinforcement learning agents outperformed myopic policies in both objective metrics of resident space objects' state uncertainties and the number of unique resident space objects observed over a 90 minute observation window. The agents' robustness to changes in orbital regimes, the observation window length and changes to the observer's location are also presented.

[View Full Paper]

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AAS 21-770

MULTI TARGET TRACKING USING A RANDOM FINITE SET STATISTICS TECHNIQUE (RFISST -II) WITH MEASUREMENT DRIVEN TRACK INITIALIZATION

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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MCMC SUBSET SIMULATION FOR PROBABILITY OF COLLISION COMPUTATION

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

It is shown that probability of collision computation using the traditional schemes which consider some time span around the time of closet approach may be incorrect by orders of magnitude for long-term engagements between two space objects. Sampling based methods are presented as a robust alternative with no such assumptions. To reduce the computational burden of simulating a large number of particles, a novel subset simulation based MCMC scheme is introduced to compute in-orbit space-object collision probability.

The collision probability is expressed as a product of larger conditional failure probabilities by introducing intermediate failure events. Well-chosen large (relative to collision probability) values of nested conditional failure probabilities can be estimated by means of simulating only a limited number of samples. The resulting efficiency and accuracy of the suggested scheme are demonstrated against independent benchmarks that use other techniques for calculating the probability of collision. Novel contributions have also been made on techniques to reduce the variance in the probability of collision results.

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RENDEZVOUS AND PROXIMITY OPERATIONS

Session Chairs:

Session 4: Robert Melton, Pennsylvania State University

Session 16: Natasha Bosanac, University of Colorado, Boulder

Session 21: John Kidd, Ascending Node Technologies, LLC

Session 26: Siamak Hesar, Kayhan Space Corp

The following paper listed in the program was not presented:

AAS 21-694

AAS 21-500

DEVELOPMENT AND EXPERIMENTAL VALIDATION OF TWO-POINT OPTIMAL GUIDANCE FOR SPACECRAFT FORMATIONS

Yazan Chihabi[*] and Steve Ulrich[†]

A novel guidance law that utilizes optimal control theory in combination with linear time-varying state-transition matrices to calculate the optimal path for a chaser spacecraft from its initial point to a desired final point and a desired amount of time is proposed in this paper. In addition, this paper presents a new method that allows for the closed-loop testing of guidance, navigation and control systems with realistic software models of GPS receivers and RADAR systems for on-board relative navigation. Specifically, utilizing the signal-to-noise ratio of various sensors, the errors that arise due hardware noise and/or environmental factors can be modeled accurately based on the communication link. The guidance law was tested using the newly developed software-in-the-loop test-bed for a far-range formation flight scenario around the non-cooperative Alouette-2 spacecraft as well as on a highly elliptical orbit.

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AAS 21-502

OPTIMAL LAUNCH AZIMUTH COMPUTATION FOR LUNAR ASCENT

Zhong-Sheng Wang*

In the study, the optimality condition of the lunar launch azimuth in a lunar orbit RVD mission was investigated. The results indicated that optimal launch azimuth can be realized when the ascent trajectory plane is perpendicular to the plane formed by the position vector of the sample site and orbital angular momentum vector of the orbiter. Based on the optimality condition of the launch azimuth, an iterative procedure was developed to compute the accurate optimal lunar launch azimuth and initial lunar orbit of the ascent module at lunar orbit insertion for practical engineering applications. A few numerical examples from Chang'e 5 mission are provided to illustrate the approach.

[View Full Paper]

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AAS 21-511

SATELLITE RELATIVE STATE UNCERTAINTY DYNAMICS IN THE VICINITY OF A POORLY TRACKED TARGET OBJECT

Ethan R. Burnett* and Hanspeter Schaub†

This paper explores the dynamics for the sensitivity of the satellite relative state to uncertainty in the initial orbit elements of the target object about which the dynamics have been linearized. These sensitivities enable rapid and highly accurate Monte Carlo analysis of the evolving uncertainty in the relative state with respect to a nearby unknown target object. The dynamics of the sensitivities are derived, and the influence of control on these quantities is investigated. Because the sensitivities directly determine the time-varying shape of the relative state distribution, the interesting concept of using control to directly influence the sensitivities is also explored. Through this framework, the uncertainty distribution of relative states can be directly influenced to some degree, which could be useful in some rendezvous and relative motion applications.

[View Full Paper]

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A UNIQUE GROUND SIMULATOR FOR ON-ORBIT SERVICE MISSION EMULATION

Anirudh Chhabra[*] and Donghoon Kim[†]

Autonomous on-orbit servicing missions require high precision because any unwanted contact forces can cause damage to space systems. This makes the on-ground hardware-in-the-loop simulations necessary as operations must be thoroughly evaluated before such missions are carried out in space. A unique robotic platform is proposed where a 3 degrees-of-freedom (DOF) robotic arm is placed atop a 6 DOF Stewart platform. A mathematical model is developed for the resulting 9 DOF redundant manipulator, and the corresponding dynamics are modeled and verified. Simulation studies are conducted using a constrained and singularity-robust pseudo-inverse control scheme, and the system's capability to follow a scaled-down orbital trajectory is tested. The results are presented, and the future implications of this study are discussed.

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AAS 21-531

DEVELOPMENT AND ANALYSIS OF A TELESCOPING PLANAR CONTINUUM MANIPULATOR FOR ON-ORBIT SATELLITE SERVICING APPLICATIONS

Nathan Dalton* and Jennifer Hudson†

Robotic on-orbit servicing is a developing technology that seeks to increase the longevity and repairability of faulty or aging resident space objects (RSOs). Ranging from propellant exhaustion, antenna deployment failure, or solar panel deployment failures to unpredictable impact damage or total satellite failure, many satellites encounter post-launch faults. In this paper, the development of a low-dexterity and flexible continuum manipulator is proposed as a contribution to a hypothetical and expendable satellite system that performs low-complexity on-orbit servicing or debris removal. The forward, inverse, and velocity kinematics of the manipulator are described in detail. The accuracy and servicing applications for the manipulator are analyzed and discussed.

[View Full Paper]

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SENSITIVITY OF SEPARATION INDICATORS IN SPACECRAFT FORMATION COLLISION RISK ANALYSIS

Ulises E. Núñez Garzón[*] and E. Glenn Lightsey[†]

The 99.73% minimum distance, denoted as $\rho_{3\sigma}$, is the 0.27%-percentile in the distribution of the norm of the instantaneous relative position between two agents. Previously, $\rho_{3\sigma}$ has been proposed as a probabilistic collision risk boundary for spacecraft formation flight under the assumption of Clohessy-Wiltshire (CW) relative orbital dynamics. In this case, agents with lesser separation than $\rho_{3\sigma}$ have an instantaneous collision probability higher than 0.27%. This work validates the foregoing interpretation of $\rho_{3\sigma}$ by showing that small changes to the target probability of $\rho_{3\sigma}$ also result in small changes to $\rho_{3\sigma}$ itself.

[View Full Paper]

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AAS 21-579

IMPULSIVE CONTROL OF FORMATIONS NEAR INVARIANT TORI VIA LOCAL TOROIDAL COORDINATES

Ian Elliott[*] and Natasha Bosanac[†]

Invariant tori relative to periodic orbits have historically been identified as a useful reference for locating spacecraft formations in multi-body environments. An impulsive control strategy is presented to enable geometric formations of spacecraft operating near periodic orbits. Toroidal coordinates that represent the relative state of a spacecraft in relation to the center eigenspace of a periodic orbit are used to develop a targeting strategy that is capable of tracking specific deviations from a periodic orbit. The presented strategy is developed using the circular restricted three-body problem and assessed in a point-mass ephemeris model of the Sun-Earth system with perturbations from solar radiation pressure.

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AAS 21-590

ON-ORBIT SERVICING LOGISTICS FRAMEWORK GENERALIZED TO THE MULTI-ORBIT CASE

Tristan Sarton du Jonchay,[*] Yuri Shimane,[*] Masafumi Isaji,[*] Hao Chen,[†] and Koki Ho[‡]

This paper proposes a multi-orbit on-orbit servicing logistics optimization frame-work capable of planning the operations of sustainable servicing infrastructures with client satellites distributed across different orbits of various shapes. The proposed framework generalizes the state-of-the-art network-based on-orbit servicing logistics optimization method to the multi-orbit case by tracking the relative motion of the network nodes as part of the process of computing the costs of the network arcs. The new framework keeps track of the simulation time in order to propagate the orbital elements of the network nodes over time. The orbital elements are then inputted into high-thrust and low-thrust trajectory optimization routines interfaced with the framework to accurately compute the cost of transportation of the servicers. Finally, a mixed-integer linear program is formulated to model the operations of the servicing infrastructure over the network and over time, whereas the rolling horizon procedure is leveraged to account for the uncertainties in service demand. Two case studies demonstrate the application of the generalized framework to the short-term operational scheduling and long-term strategic planning of on-orbit servicing infrastructures.

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ASTRODYNAMICS-INFORMED KINODYNAMIC MOTION PLANNING FOR RELATIVE SPACECRAFT MOTION

Taralicin Deka* and Jay McMahon†

Motion Planning is a computational problem that seeks its solution as a sequence of actions that can safely guide a robot/object from a given initial state to a set of final states. Traditional guidance algorithms in the field of astrodynamics, like the Lambert's solution, compute the transfer orbit for a spacecraft between two given position vectors. But such algorithms do not come with collision-avoidance capabilities. For the purpose of this work, we seek a computationally efficient motion planning technique that can be implemented on-line for astrodynamics problems subject to kinodynamic (simultaneous kinematic and dynamics) constraints. We leverage the theoretical advancement in the field of sampling-based motion planning and present an Astrodynamics-informed kinodynamic motion planning (AIKMP) algorithm that takes advantage of a spacecraft's natural motion to compute a fuel-efficient and collision-free trajectory. We show that, by augmenting sampling-based motion planning algorithms with knowledge of astrodynamics, fuel-efficient and collision-free motion planning can be achieved in astrodynamics applications.

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AAS 21-594

HELIOSWARM: RELATIVE ORBIT MAINTENANCE IN ECCENTRIC P/2 LUNAR RESONANT ORBIT

Paul Levinson-Muth,[*] Laura Plice,[†] and Jose Alvarellos[‡]

Science missions employing multi-point measurements require planned and repeatable swarm geometries. Cis-lunar orbits enable heliophysics studies of solar wind but introduce new challenges in relative motion control. For a multi-satellite swarm in lunar-resonant orbit, insertion and maintenance maneuvers address orbit eccentricity and evolution, as well as three-body gravitational perturbations. Local Velocity-Normal-Conormal coordinates prove to be an effective framework for relative motion design and control. Parametric studies investigate maneuver placement and efficiency in controlling relative motion in cis-lunar orbit.

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CARTESIAN RELATIVE MOTION ON PERTURBED ECCENTRIC ORBITS AND CLOSED-FORM SOLUTION FOR J2 EFFECTS AT LOW INCLINATIONS

Matthew Willis* and Simone D'Amico†

Two contributions to the study of perturbed relative motion in the radial-transverse-normal frame of an eccentric orbit are introduced. First, a general form of the governing equations is developed, allowing for any perturbation and choice of independent variable. Next, these are simplified and solved for the practical case of equatorial orbits subject to Earth oblateness perturbation. This results in a novel analytical solution that is shown to be orders of magnitude more accurate than other translational state models in the literature. The new solution is evaluated across a wide range of eccentricities and inclinations, and is applicable to hyperbolic trajectories as well as elliptical orbits.

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DUAL LIE ALGEBRA REPRESENTATIONS OF RIGID BODY DISPLACEMENT AND MOTION. AN OVERVIEW (I)

Daniel Condurache*

The parameterization of a rigid-body motion can be done using multiple algebraic entities. Therefore, a crucial criterion when choosing a parameterization method is the number of algebraic equations and variables. Recently, orthogonal dual tensors and dual quaternions proved to be a complete tool for computing rigid-body displacement and motion parameters. This research's main goal is to develop a new minimal parameterization technique for rigid-body displacement and motion. Our study is based on the properties of dual tensors, more precisely their Lie group and Lie algebra. As a result, for the first time, a complete parameterization framework is constructed, which gives the possibility of developing unitary direct solutions for computation of the main motion kinematic representation entities: Euler dual vector, Rodrigues dual vector, Wiener Milenkovic dual vector, Euler-Rodrigues dual parameters, and dual quaternions. Furthermore, based on higher-order modified Cayley transforms, dual orthographic projection, dual Lambert parameters, dual Breusing parameters, and dual sin family parameters are introduced.

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AAS 21-631

ESTIMATION ERROR COVARIANCE CONTROL FOR SPACECRAFT FORMATION FLYING

Kaushik Prabhu,[*] Kyle T. Alfriend,[†] and Amir Rahmani[‡]

We study the spacecraft relative motion estimation problem using Extended Kalman filters based on two dynamic models, the Clohessy-Wiltshire and the Gim-Alfriend state transition matrix. A sensor capable of switching between angles-only and range-only measurement modes is assumed to be on-board. The behaviour of the estimation error covariance mapped to the measurement space is studied for the partially observable system. For accurate estimation, a simple logic for switching between the measurement modes based on the measurement-space covariance is presented. Using a high-fidelity simulation environment, it is shown that the filter based on the Gim-Alfriend dynamic model provides more accurate estimates while requiring less frequent measurement switching as compared to the filter based on the Clohessy-Wiltshire dynamic model.

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AAS 21-632

GUIDANCE AND CONTROL OF ORBIT BERTHING MANEUVERS VIA FEEDBACK LINEARIZATION*

Ivan Napoli† and Mauro Pontani‡

This research proposes an effective guidance, control, and actuation architecture for close-range maneuvering of a chaser spacecraft toward a target vehicle, aimed at orbital berthing. The chaser vehicle is equipped with a single thruster (for trajectory corrections) and an array of single-gimbal control momentum gyroscopes (for attitude control). The relative dynamics of the two vehicles, placed in nearby low Earth orbits, is modeled using the (exact) nonlinear Battin-Giorgi equations of relative motion, with the inclusion of all the relevant perturbations, i.e. several harmonics of the geopotential, atmospheric drag, and solar radiation pressure. Feedback linearization is used as an effective real-time technique, to identify the thrust direction and magnitude needed to drive the chaser toward the target. The commanded attitude, associated with the desired thrust direction, is pursued using a nonlinear attitude control algorithm, which enjoys quasi-global stability. The steering law of the actuation devices is based on the Moore-Penrose pseudoinverse, with singular value decomposition of the actuation matrix. Monte Carlo simulations prove effectiveness and accuracy of the guidance and control architecture at hand, in the presence of nonnominal flight conditions, related to random initial attitude and stochastic navigation errors.

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AAS 21-640

POSE TERRIER - IMAGE-BASED POSE ESTIMATION AND FILTERING FOR SPACECRAFT APPLICATIONS

Siddarth Kaki[*] and Maruthi R. Akella[†]

The problem of estimating relative pose for uncooperative space objects has garnered great interest, especially within applications such as asteroid mapping and satellite servicing. This work presents Pose Terrier, an open-source, relative pose estimation and filtering software package written in C++ for space systems applications. Pose Terrier consists of two main components: 1) a pose estimation component, implementing both nonlinear least-squares and perspective-n-point solvers, and 2) a full-pose tracking component, implementing a multiplicative extended Kalman filter. Even though Pose Terrier is designed to be a general-purpose solution, its development was motivated by the needs of the NASA Seeker cubesat program.

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AAS 21-645

DERIVATION OF VARIATIONAL EQUATIONS FOR THE LOVELL-SPENCER RELATIVE ORBITAL ELEMENT SET

Michael R. Thompson*

Previous studies of relative orbital elements have shown their usefulness in providing straightforward geometric interpretations of relative spacecraft motion. This paper applies concepts of general perturbations theory to the Lovell-Spencer relative orbital element formulation. A form of the Lagrange Planetary Equations is derived specifically for these relative orbital elements along with a set of variational equations. These equations give time derivatives for each element as a function of perturbing accelerations on the secondary spacecraft in the primary spacecraft's body-fixed frame. To validate this derivation and demonstrate applications, examples are shown of adjusting the relative orbit of two spacecraft in GEO.

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AAS 21-648

SPACECRAFT RENDEZVOUS IN CLOSED KEPLERIAN ORBITS USING LOW RADIAL THRUST

Siddarth Kaki[*] and Maruthi R. Akella[†]

An analytical solution for spacecraft rendezvous within closed Keplerian orbits is presented using low radial-thrust. The two spacecraft are assumed to be initially placed within the same closed orbit with arbitrary phase angle separation. The target spacecraft is assumed to always remain in the same initial orbit. The chaser vehicle, however, uses a judiciously designed maneuver sequence comprised of constant-acceleration low radial-thrust phases interspersed with coast phases. Importantly, the proposed maneuver design is analytically characterized by a single nonlinear algebraic equation that determines the time-intervals for the different phases. However, the solution is suboptimal in terms of time and fuel-use.

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OUTLIER-ROBUST MULTI-VIEW TRIANGULATION USING GRADUATED NON-CONVEXITY FOR SPACE VEHICLE NAVIGATION

Adriana Mitchell* and Richard Linares†

Triangulation is used in terrain relative navigation (TRN) to identify the position of terrain features with respect to the spacecraft and to ultimately estimate the spacecraft's pose during planetary landing and navigation. This work seeks to improve current multi-view triangulation methods to optimally perform with an outlier-dominant (>50% outlier) dataset. Outlier-dominant situations may occur in cases of extreme environmental changes (poor lighting conditions, obscured vision), unreliable sensors, and in the case of TRN, incorrect feature matching. We show that current multi-view triangulation solvers fail at >=10% outlying measurements. We apply Yang et al.'s (2020) Graduated Non-Convexity (GNC) algorithm to three chosen multi-view triangulation solvers and improve the best performing solver's robustness to >50% outliers which outperforms the current state-of-the-art outlier removal method RANSAC. We apply the robust multi-view triangulation solver to a simulated lunar landing trajectory from synthetic lunar images and reported the variance of the returned 3D error to verify the accuracy of the estimate. This new technique of making current multi-view triangulation solver robust to outliers using GNC provides exciting performance and displays promise for future implementation on a TRN system. This combination has not been shown before in previous work, but this work enables the conclusion that efficient outlier-robust methods can be applied to TRN.

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ROBOTIC TESTBED FOR RENDEZVOUS AND OPTICAL NAVIGATION: MULTI-SOURCE CALIBRATION AND MACHINE LEARNING USE CASES

Tae Ha Park,* Juergen Bosse,† and Simone D'Amico‡

This work presents the most recent advances of the Robotic Testbed for Rendezvous and Optical Navigation (TRON) at Stanford University - the first robotic testbed capable of validating machine learning algorithms for spaceborne optical navigation. The TRON facility consists of two 6 degrees-of-freedom KUKA robot arms and a set of Vicon motion track cameras to reconfigure an arbitrary relative pose between a camera and a target mockup model. The facility includes multiple Earth albedo light boxes and a sun lamp to recreate the high-fidelity spaceborne illumination conditions. After the overview of the facility, this work details the multi-source calibration procedure which enables the estimation of the relative pose between the object and the camera with millimeter-level position and millidegree-level orientation accuracies. Finally, a comparative analysis of the synthetic and TRON simulated imageries is performed using a Convolutional Neural Network (CNN) pre-trained on the synthetic images. The result shows a considerable gap in the CNN's performance, suggesting the TRON simulated images can be used to validate the robustness of any machine learning algorithms trained on more easily accessible synthetic imagery from computer graphics.

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DUAL-PARAMETER STABILIZED CONTROL OF SPACECRAFT FORMATIONS WITH COMBINED SOLAR RADIATION PRESSURE AND THRUSTERS USING GUARDIAN MAPS

Yazan Chihabi* **and Steve Ulrich†**

This paper presents a new control law that combines solar radiation pressure as a form of actuation with thrusters to reduce the fuel necessary to perform formation reconfiguration and maintenance. Specifically, utilizing the dual-parameter stabilization technique of Guardian Map theory, a control law that is robust to changes in orbital position and angle with respect to the sun-vector is proposed. A linear parameter varying model of the chaser spacecraft that considers the effects of a third-body, and the nonlinear model of solar radiation pressure is also proposed in this paper and used in the development of the control law. Results show a reduction in fuel-consumption during the transients of formation reconfiguration and maintenance.

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ATTITUDE RECONSTRUCTION OF AN UNKNOWN CO-ORBITING SATELLITE TARGET USING MACHINE LEARNING TECHNOLOGIES

Ben Guthrie,[*] Minkwan Kim,[†] Hodei Urrutxua,[‡] and Jonathon Hare[§]

Active debris removal missions pose demanding guidance, navigation and control requirements. We propose that novel machine learning techniques can help to meet several of the outstanding requirements. Building upon previous work which adopts machine learning technologies for tracking the rotational state of an unknown and uncooperative debris satellite, we improve the approach by further applying machine learning to make use of past measurements. The attitude of the debris target is reconstructed, thereby enabling different debris removal methods. The construction of a simulation framework for generating accurate labelled image data is presented, with the aim of facilitating further research in this area. Finally, we show that a neural network can also learn to track satellites and identify suitable locations for contact-based removal methods, without a-priori knowledge of the object's geometry.

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PERFORMANCE ANALYSIS OF DECENTRALIZED ESTIMATION ALGORITHMS FOR COOPERATIVE LOCALIZATION IN SPACECRAFT SWARMS

Nobuhiro Funabiki,* Satoshi Ikari,† Ryu Funase,‡ and Shinichi Nakasuka§

Cooperative localization is one of the essential technologies for spacecraft swarm systems to enable advanced and coordinated multi-agent operations. To enhance the scalability of a localization algorithm, decentralization approaches have been widely studied for spacecraft swarms. This paper investigates how the estimation algorithms with different centralized/decentralized architectures affect their estimation performances, including accuracy, stability, and communication costs. Furthermore, the trade-off relationship of the performance-related parameters and the principle to select a proper estimation architecture are discussed through the numerical simulations.

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LYAPUNOV-FLOQUET TRANSFORMATION OF J_2 PERTURBED SPACECRAFT FORMATION FLYING WITH PERIODIC COEFFICIENTS

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

In this paper, Lyapunov-Floquet (LF) transformation, a powerful technique for the analysis of nonautonomous and periodic linear and nonlinear differential equations, is employed for the analysis of spacecraft formation flying dynamics under the effect of J_2 perturbation force. For better relative motion analysis J_2 perturbation force is included in the equation of motion and, with chief spacecraft in elliptical orbit, unlike the case of circular orbit, the differential equation of motion becomes time varying and periodic. Approximated J_2 perturbed nonlinear spacecraft relative motion equation is extracted from the original nonlinear equation and then converted into a form amenable for the application of Lyapunov-Floquet transformation. Through the application of LF transformation the J_2 perturbed approximated equation is converted into constant coefficient linear equation and time-varying and periodic nonlinear terms. This form is usable for designing fuel efficient control strategy for spacecraft formation flying, spacecraft relative motion and rendezvous mission design.

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DEVELOPMENT OF NORMAL FORM OF SPACECRAFT RELATIVE MOTION VIA NONLINEAR COORDINATE TRANSFORMATIONS

Ayansola D. Ogundele* and Olufemi A. Agboola†

The correct choice of coordinates is central to the understanding of many problems in dynamical systems theory. The normal form method, a key tool for the local analysis of dynamical systems, is primarily concerned with finding a coordinate system in which the dynamical system assumes the simplest form with reduced system of equations. The nonlinear coordinate transformation preserves the essential features of the system. The normal form main idea is to find polynomial which improves locally a nonlinear system in order to analyze its dynamics more easily and to give a better insight. Generally, analysis of the relative motion of deputy spacecraft relative to the chief spacecraft in circular orbit is usually done using Hill-Clohessy-Wilshire (HCW) and in elliptical orbit using Tschauner-Hempel (TH) equations. The beneficial nonlinear terms were neglected in the development of both models. In this paper, an approximated relative motion equation containing cubic nonlinear terms is developed. Afterward, the approximated equation is analyzed using normal form, modal transformation and near identity transformation. The nonlinear equations are simplified by eliminating as many nonlinear terms as possible, while keeping the linear part unchanged. The structure of the normal form of the cubic model is determined entirely by the nature of the linear part of the relative motion dynamics. The normal form developed can be applied for the control of spacecraft relative motion, spacecraft formation flying and rendezvous missions.

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NONLINEAR MAPPING OF J_2 PERTURBED RELATIVE MOTION FOR SPACECRAFT RENDEZVOUS, FORMATION FLYING AND PROXIMITY MISSIONS

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

The classical Keplerian orbit motion, a two-body problem involving the movement of one body (e.g. spacecraft) under the effect of a central Newtonian force as given by a gravitational force of a second massive body (e.g. the Earth), is a hypothetical motion which does not represent, in reality, the actual motion of the body. A high fidelity representation of the motion is obtained by the inclusion of perturbation forces such as J_2 perturbation, third-body perturbation, solar radiation and atmospheric drag. Exclusion of the perturbation forces will lead to more fuel usage because of the need for frequent corrections of the relative orbit. In this paper, the Hill position and velocity coordinates are nonlinearly mapped to the orbit element differences between the Chief and Deputy spacecraft under the effect of J_2 perturbation force. Unlike as in the case of linear mapping, the new nonlinearly mapped radial, along-track and cross-track positions and velocities and orbit element differences have the advantage of being able to give a better insight into the dynamics of spacecraft relative motion with larger separation. The resulting model is validated against the existing models through numerical simulations. The new model is useful for spacecraft rendezvous, formation flying and proximity operations.

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AAS 21-708

COMPLETE RELATIVE MOTION ANALYSIS ON QUASI-PERIODIC ORBITS VIA DISCRETE FOURIER TRANSFORM MAP

Chihang Yang* and Hao Zhang†

A general approach is proposed to completely analyze the relative motion on quasi-periodic orbits. This approach is based on a fundamental property that the angle difference between two arbitrary spacecraft on the same quasi-periodic orbit remains constant during the evolution. Therefore, given the angle difference, all possible relative states can be fast evaluated by traversing the space of phase angles of a single reference spacecraft via a discrete Fourier transform map. Hence, arbitrarily relative motion characteristics can be completely analyzed and furthermore guide formation designs. Analysis results of formations on quasi-DRO and quasi-halo orbits show the capability of the proposed approach.

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TRAJECTORY PLANNING AND IMPEDANCE CONTROL OF A DUAL-ARM SPACE ROBOT FOR ON-ORBIT CAPTURING

Xinhui Xia* **and Yinghong Jia†**

This paper mainly presents an improved trajectory planning and impedance control method of a dual-arm space robot system to capture a space target with a 3-dimensional contact dynamics considered. The contact between the arms terminal parts (i.e. the end effectors) and the target is modeled in accordance with a spring-dashpot model at the moment of capture. An online trajectory planning method based on position-based visual servoing is proposed to obtain the desired pose of the end effector. Finally, a trajectory tracking control is designed using the impedance control algorithm. Simulation results demonstrate the effectiveness of the proposed control scheme.

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AAS 21-711

OPTIMAL STRATEGIES FOR ALTITUDE AND TIME-CONSTRAINED ON-ORBIT RENDEZVOUS

Daniel Jang,* David Arnas,† and Richard Linares‡

In this work we study the optimal orbital maneuvers for an on-orbit servicing satellite to rendezvous with a set of client spacecrafts. With the growth of LEO mega-constellations, various types of Space Traffic Management schemes are being proposed. For on-orbit servicer concepts, efficient transfer between different clients will be necessary, and any altitude constraints will pose a real operational limitation. For plane change maneuvers – such as RAAN changes within a shell – we propose the use of the differential effect of the J2 perturbation between the spacecrafts to perform the orbital maneuvers and reduce the required amount of fuel. In this paper, we explore different approaches for in-plane phase changes. These servicing strategies are assessed for a range of distribution of servicers and their maneuvers with active time and altitude-band constraints. Orbital servicing tradespace is explored generally, then applied for the recently proposed telecommunication satellites utilizing LEO constellations such as Amazon Kuiper, SpaceX Starlink and OneWeb.

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AAS 21-722

LONG TERM AND SAFE RECONFIGURATION FOR SPACECRAFT CLUSTERS

Burak Yaglioglu[*] and Ozan Tekinalp[†]

The problem of spacecraft cluster reconfiguration with realistic operational considerations is addressed. Here, a reconfiguration algorithm is developed to maximize station keeping and safety objectives while minimizing the total maneuvering effort. For station keeping objective, sequential cluster configurations are found by minimizing deviations from a reference mean orbit for long time intervals. In addition, these configurations are verified for safety by propagating the spacecraft with a high precision propagator and monitoring probability of collision within the cluster. Then spacecraft are associated into new configurations using auction algorithm which minimizes total maneuvering effort. Effectiveness of the algorithm is demonstrated through simulations.

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AAS 21-735

PRELIMINARY ANALYSIS OF THE GRAVITATIONAL PERTURBATIONS FROM EARTH OVER A CO-ORBITAL FORMATION FLYING

Josué Cardoso dos Santos,[*] Willer Gomes dos Santos,[†] Lamberto Dell'Elce,[‡] and Artur Robson Cutolo[§]

The present work intends to analyze the gravitational dynamics under which a formation flying mission as the one proposed by the ITASAT-2 project is subjected. The type of dynamics analyzed here and involving this type of mission considers a low-altitude orbit for the spacecraft and with significant disturbing effects coming from the Earth's irregular gravitational field. The mapping of different initial conditions under different number of disturbing potentials is performed to evaluate their contribution over the dynamics of different satellites in a co-orbital formation flying. The different dynamical configurations considered are in terms of different semimajor axes and orbital inclinations. Regions with more and less oscillations over important orbital elements are identified when the satellites of the formation are compared. The results will support the planning of the ITASAT-2 mission and can guide other similar types of projects which use similar type of dynamics.

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AAS 21-757

ANALYSIS OF ACTUATORS AND SENSORS NONLINEARITIES IN A SPACECRAFT FORMATION FLYING MISSION

Rodrigo D. Dias,[*] Willer G. dos Santos,[†] Josué C. dos Santos[‡]

Spacecraft formation flying is a key technology for complex space missions. The main goal of this study is to analyze how the nonlinearities of satellite's actuators and sensors can interfere in a formation flying mission. Simulations were performed varying the sensor's bias and noise as well as a constant of time and time delay of actuators. Results show that these factors can provide a better understanding of the system behavior and also a sense of the amount of fuel consumed on the mission.

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AAS 21-760

MODELING OF AN ON-ORBIT MAINTENANCE ROBOTIC ARM TEST-BED

Jacob J. Korczyk,[*] Daniel Posada,[†] Aryslan Malik,[‡] and Troy Henderson[§]

This paper focuses on the development of a ground-based test-bed to analyze the complexities of contact dynamics between multibody systems in space. The test-bed consists of an air-bearing platform equipped with a 7 degrees-of-freedom (one degree per revolute joint) robotic arm which acts as the servicing satellite. The dynamics of the manipulator on the platform is modeled as an aid for the analysis and design of stabilizing control algorithms suited for autonomous on-orbit servicing missions.

The dynamics are represented analytically using a recursive Newton-Euler multibody method with D-H parameters derived from the physical properties of the arm and platform. In addition, Product of Exponential (PoE) method is also employed to serve as a comparison with the D-H parameters approach. Finally, an independent numerical simulation created with the SimScapeTM modeling environment is also presented as a means of verifying the accuracy of the recursive model and the PoE approach. The results from both models and SimScapeTM are then validated through comparison with internal measurement data taken from the robotic arm itself.

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AAS 21-767

ANALYSIS OF MODELS FOR RELATIVE DYNAMICS OF A LUNAR FORMATION FLYING

Artur Robson Cutolo,[*] Josué Cardoso dos Santos,[†] Willer Gomes dos Santos,[‡] and Luiz Arthur Gagg Filho[§]

The Moon is considered essential to unlock the evolutionary history of the planets because it preserves a surface record that covers most of the history of the solar system and is easily accessible from the Earth. It is also a key celestial body when one thinks of human exploration of the Solar System and its resources. Among the best methods available for its study is the use of small satellites orbiting this celestial body. In this context, it is possible to consider the use of several satellites in lunar formation flying which, with a significantly lower cost, can provide greater lunar coverage than if compared to a single large satellite. Thus, in order to explore the applications of temporal relative motion solutions of high-order (ES Model), second-order (2O Model), and first-order/Hill solution (H Model), the present work aims to analyze these models often used for formation flying of Earth satellites. We have considered here the relative dynamics between a Chief and a Follower satellite around the Moon, where variations of different orbital parameters are performed to map errors and identify accuracy regions for each dynamical model.

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6DOF NONLINEAR GUIDANCE FOR SPACECRAFT FORMATION FLYING

Hermann Kaptui Sipowa[*] and Jay McMahon[†]

This work introduces a novel path planning algorithm that leverages natural forces such as differential solar radiation pressure (SRP) to generate fuel-free transfer trajectories for Earth-orbiting spacecraft formations. The problem studied is a relative guidance problem. A flat plate deputy spacecraft changes its attitude to fly fuel-free around a cannonball chief spacecraft using differential solar radiation pressure. First, the controllability of the 6DoF guidance problem is assessed using lie bracket theory. Then, a fuel-free path is generated using a manifold shaping method based upon Riemannian geometry. The computed paths are chosen to be the geodesics of the solution manifold.

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AAS 21-513

NOVEL CO–ORBITAL STABILITY REGION AND PERIODIC ORBITS IN THE EARTH–MOON SYSTEM

Kenta Oshima*

The first part of this paper reveals a stability region near the 1 : 1 retrograde resonance with the Moon. Three families of periodic orbits are identified as the possible origin of the stability region. Ballistic capture trajectories into the stability region from the vicinity of the Earth and interplanetary space exist. The second part explores the use of the retrograde periodic orbits around the Earth for spacecraft trajectories. Capture, escape, and stationkeeping analyses lead to a concept "Comet Interception from eArth retrOgrade orbIT viA Lunar gravIty Assist" using the retrograde periodic orbit as a staging post and enabling fast lunar encounters to travel toward interplanetary space.

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AAS 21-519

IMPLEMENTATION OF MACHINE LEARNING METHODS FOR CRATER-BASED NAVIGATION

Sofia G. Catalan,[*] James S. McCabe,[†] and Brandon A. Jones[‡]

Developing autonomous navigation capabilities enable spacecraft to rely less on Earth-based tracking and communications resources. Optical navigation during dynamic mission phases provide a local method of updating state estimates, given an image processing capability that can extract surface features for an onboard filter to process. This paper presents a machine learning based approach for crater detection, which implements a Mask Region-based Convolutional Neural Network to process lunar imagery. With an automated labeling process to generate datasets and an iterative training approach, the developed crater detector is tested against simulated and real images to provide an assessment of the detection performance. Integrated results from a navigation simulation are also included to show the state estimation accuracy given the current capabilities of the crater detector.

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AAS 21-528

ORBIT DESIGN ELEMENTS OF THE LUNAR SAMPLE RETURN MISSION

Zhong-Sheng Wang,[*] Zhanfeng Meng,[†] Shan Gao,[‡] and Jing Peng[§]

The three key orbit design technologies employed in the Chang'e 5 mission are identified and discussed in this paper: orbit design for lunar orbit rendezvous and docking, orbit design for precision lunar landing and inclination optimization, and orbit design for Moon-to-Earth transfer. First, an overview of the Chang'e 5 mission profile is presented, which is followed by detailed discussions of the three key orbit design technologies, including an introduction of the tracking-based orbit design methodology. Flight data are provided to demonstrate the correctness of the designs.

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AAS 21-580

USING MOTION PRIMITIVES TO DESIGN LIBRATION POINT ORBIT TRANSFERS IN THE EARTH-MOON SYSTEM

Thomas R. Smith[*] and Natasha Bosanac[†]

Motion primitives offer a summary of the diverse and complex solution space within a multi-body system. In this paper, sets of motion primitives, as well as their corresponding regions of existence, are leveraged to facilitate rapid identification of suitable trajectory segments for initial guess construction. To develop a continuous solution from an initial set of primitives, a constrained optimization approach that leverages a direct collocation scheme is formulated to compute libration point orbit transfers in the Earth-Moon circular restricted three-body problem. This primitive-based initial guess construction strategy limits the analytical burden on a human designer and supports rapid trajectory design.

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AAS 21-581

MULTI-REVOLUTION EXTENSION OF SOLAR-PERTURBED MOON-TO-MOON TRANSFER FAMILIES

Burton Yale* and Gregory Lantoine†

Lunar flybys and solar perturbations present a golden opportunity to naturally modify trajectories of spacecraft launched in Moon-bound orbits. Leveraging the energy gained, or lost, from lunar flybys and multi-body effects allows for spacecraft to reach destinations not previously within their designed Δv budgets. Previous research studies have demonstrated the viability of collecting zero revolution Moon-to-Moon transfers into a referential database. This paper extends this capability to multi-revolution transfers and describes their main characteristics and increased versatility. Finally, a trajectory example is given for the escape phase of the NEA Scout mission.

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AAS 21-582

AN INVESTIGATION OF TERRAIN RELATIVE NAVIGATION FOR THE LUNAR GATEWAY

Michael T. Caudill* **and Jay W. McMahon†**

With the selection of a lunar near-rectilinear halo orbit (NRHO) as the operational orbit for the upcoming Gateway mission, orbit determination and navigation strategies for Gateway have been a targeted area of research in the recent past. Advancements in spaceflight technology are better equipping spacecraft to support autonomous navigation, alleviating sole dependence on ground-based radars and hardware. This work develops an orbit determination methodology using simulated terrain-relative measurements and compares its performance to Deep Space Network (DSN) tracking. The terrain-relative orbit determination methodology is employed for the estimation of Gateway's orbital state and construction of orbit maintenance maneuvers to maintain bounded operations about a nominal trajectory.

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AAS 21-584

DATA-DRIVEN ANALYSIS OF CHAOTIC ORBITS IN THE CIRCULAR RESTRICTED THREE BODY PROBLEM

Urashi Taiki,[*] Bando Mai,[†] and Hokamoto Shinji[‡]

This paper analyzes ballistic lunar transfers known as chaotic orbits by using a data-driven approach called HAVOK (Hankel Alternative View of Koopman). HAVOK is a method to decompose a chaotic dynamical system into a linear model with intermittent forcing, and it has a possibility to reveal the chaotic dynamical system. In this analysis, it is demonstrated that chaotic orbits can be reconstructed by HAVOK, and the transport mechanism between Earth and Moon regions is found by classifying the magnitude of the intermittent forcing. In addition, the relation between the transport mechanism obtained by HAVOK and the dynamical structure of the circular restricted three-body problem is revealed by periapsis Poincaré map.

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AAS 21-592

ECLIPSE MITIGATION STRATEGIES IN P/2 LUNAR RESONANT ORBITS

Paul Levinson-Muth,[*] Andres Dono,[†] and Laura Plice[‡]

Lunar resonant orbits present several important challenges in terms of trajectory design, insertion, stability and eclipse mitigation. For some mission concepts, the placement of the initial orbital elements is fundamental to overcoming show-stopping performance values such as eclipse duration and orbit lifetime. Lunar resonant orbits need to maintain specific alignments in order to avoid undesired flybys or even recontact with Earth or GEO satellites. This paper presents methods to mitigate long eclipses while preserving achievable lunar resonant orbits that persist in the long term.

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STOCHASTIC OPTIMIZATION FOR STATIONKEEPING OF NEAR RECTILINEAR HALO ORBITS USING A HIGH-ORDER TARGET POINT APPROACH

Xiaoyu Fu,[*] Nicola Baresi,[†] and Roberto Armellin[‡]

Near Rectilinear Halo Orbits (NRHOs) are orbits of great interest for the upcoming lunar missions. To maintain NRHOs in a three-body regime, a stationkeeping strategy based on a high-order Target Point Approach (TPA) is proposed, where fuel-optimal and error-robust TPA parameters are acquired from stochastic global optimization. Accurate TPA maneuvers are calculated in a high-order fashion enabled by Differential Algebra (DA) techniques. Stochasticity is handled by incorporating Monte Carlo simulations in the process of optimization and the evaluation of high-order ODE expansions is employed to supplant the time-consuming numerical integration. Multiple candidate NRHOs with different stability properties are investigated.

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AAS 21-630

CLOSED-LOOP NEURAL CONTROL FOR THE FINAL PHASE OF A CISLUNAR RENDEZVOUS

Giangregorio Tofanelli,[*] Giordana Bucchioni,[†] and Mario Innocenti[‡]

The paper presents the design of a closed loop controller based on neural networks for the final rendezvous in a three body problem scenario with full six degrees of freedom dynamics. The reference scenario is a rendezvous maneuver between an active chaser and a passive target located on a near rectilinear halo orbit around the L2 Lagrangian in the Earth - Moon system. The guidance system synthesis is performed using "imitation learning" with two neural networks for attitude and translation. The performance of the controllers is evaluated with respect to a standard PID approach, as well as a high frequency, high performance state dependent Riccati equation algorithm, in order to evaluate the size of the learning database and capabilities of the two networks.

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MULTI-OBJECTIVE REINFORCEMENT LEARNING FOR LOW-THRUST TRANSFER DESIGN BETWEEN LIBRATION POINT ORBITS

Christopher J. Sullivan,* Natasha Bosanac,† Alinda K. Mashiku,‡ and Rodney L. Anderson§

Multi-Reward Proximal Policy Optimization (MRPPO) is a multi-objective reinforcement learning algorithm used to construct low-thrust transfers between periodic orbits in multi-body systems. Previous implementations of MRPPO have relied on a predefined reference transfer to successfully train each policy. In this paper, an algorithmic modification labeled the 'moving reference', is introduced to autonomously construct these reference trajectories during training. With this modification, MRPPO is used to recover various low-thrust transfers between two periodic orbits in the Earth-Moon circular restricted three-body problem to solve a multi-objective optimization problem. These results are then compared with the solutions recovered via a gradient descent optimization scheme to validate the performance of MRPPO with the moving reference modification.

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AAS 21-637

RIDESHARING OPTIONS FROM GEOSYNCHRONOUS TRANSFER ORBITS IN THE SUN-EARTH SYSTEM

Juan A. Ojeda Romero* and Kathleen C. Howell†

Ridesharing options for secondary payloads to be delivered to regions beyond geostationary altitude are increasingly available with propulsive EELV Secondary Payload Adapter (ESPA) rings. However, mission design for secondary payloads faces certain challenges. A significant mission constraint for a secondary payload is the dropoff orbit orientation, as it is dependent on the primary mission. In this analysis, assume that the dropoff orbit is an Earth-centered Geosynchronous Transfer Orbit (GTO). Then, efficient transfers to orbits near the Sun-Earth L_1 Lagrange point are constructed from a range of GTO orientations. Dynamical structures, such as stable invariant manifolds, associated with periodic and quasiperiodic orbits near Sun-Earth L_1 are leveraged to identify and summarize types of transfer opportunities.

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AAS 21-642

A PRELIMINARY EXPLORATION OF PATH PLANNING FOR INITIAL GUESS CONSTRUCTION IN MULTI-BODY SYSTEMS

Kristen L. Bruchko* and Natasha Bosanac†

Constructing trajectories in multi-body systems currently relies heavily on a human analyst and, in scenarios may become time-consuming and challenging. Path planning techniques offer one approach to summarizing the solution space and autonomously generating trajectories. In this paper, roadmap generation is used to summarize the solution space. Then, a graph search algorithm is used to construct an initial guess for a transfer. This approach is explored in the context of transfers between L_1 and L_2 Lyapunov orbits in the Earth-Moon circular restricted three-body problem.

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AAS 21-668

GLOBAL TRAJECTORY OPTIMIZATION OF EARTH-NRHO TRANSFER VIA MULTIPLE IMPULSIVE MANEUVERS USING GPU-BASED HIGHLY PARALLEL ARCHITECTURE

Satoshi Ueda[*] and Hideaki Ogawa[†]

This paper presents a framework for global trajectory optimization via a multi-fidelity approach utilizing a GPU for a low-fidelity initial solution search and a CPU to determine feasible high-fidelity solutions. The proposed multi-fidelity approach enables global trajectory optimization of an Earth-NRHO transfer consisting of trans-lunar and cislunar phases via multiple impulsive maneuvers. The knowledge and insights are summarized for the resultant global structure and characteristics of the feasible solutions, while verifying the capability and effectiveness of the global design framework enabled by a GPU-based highly parallel architecture.

[View Full Paper]

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AAS 21-698

GEOMETRIC APPROACH TO THE DESIGN OF LUNAR-GRAVITY-ASSISTED LOW-ENERGY EARTH-MOON TRANSFERS

Anastasia Tselousova,[*] Sergey Trofimov,[†] Maksim Shirobokov,[‡] and Denis Perepukhov[§] [**]

Based on the previously obtained database of planar ballistic lunar transfer trajectories in the bicircular four-body problem (BR4BP) model, we apply several conventional analytical tools for the design of high-energy gravity-assist maneuvers in order to map the required (i.e., corresponding to a certain ballistic transfer) conditions on the boundary of the region of prevalence (an analog of the sphere of influence concept in the BR4BP) to the parking orbit departure parameters providing an intermediate lunar flyby to achieve such conditions. Obtained analytical estimates enable avoiding dependence on a specific near-Earth parking orbit in the early stages of mission design and represent the departure parameters corresponding to lunar-gravity-assisted ballistic transfer trajectories within the framework of the patched conic approximation model. These parameters are subsequently refined when adapting a trajectory to more complex models of motion by the multiple-shooting procedure.

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AAS 21-707

EARTH-MOON MULTI-BODY ORBITS TO FACILITATE CISLUNAR SURVEILLANCE ACTIVITIES

Maaninee Gupta,* Kathleen C. Howell,† and Carolin Frueh‡

As human interest expands outward towards the Moon again, there exists a growing focus on Space Domain Awareness to effectively regulate and track objects in the cislunar region. This investigation explores orbits in the Circular Restricted Three-Body Problem that offer behaviors that are favorable to adequately survey cislunar space between the Earth and the Moon. Resonant orbits that provide repeating geometries in an operationally stable environment are introduced. Poincaré maps are employed to leverage invariant manifolds associated with libration point orbits for transfer trajectory design. Access between the lunar vicinity and the geostationary region is facilitated via the proposed orbits.

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AAS 21-710

MASTEN XL-1 LUNAR LANDER: MISSION DESIGN AND GN&C ARCHITECTURE

Eva Pettinato,[*] Scott Nietfeld,[†] T. Emerson Oliver,[‡] Christoper Rabotin,[§] Trev Sheerin,[**] Alison Dufresne,[††] and David Masten[‡‡]

In April 2020, as part of its Commercial Lunar Payload Services (CLPS) program, NASA awarded Masten Space System $75.9 million to land on the lunar South Pole. (1) Landing on the South Pole is particularly interesting because there are areas of permanent light and permanent shadow, which leads to sufficient temperature differentials to help find water on the moon. The technological advancements made through multiple inexpensive missions will assist in getting humans to the moon quickly and safely. Masten Space Systems is a space technology company that specializes in vertical take-off and vertical landing vehicles (VTVL), more commonly referred to as landers. Through CLPS, Masten will provide end-to-end lunar services for lunar payloads. This necessitated a design of a new lander, XL-1. This paper aims to introduce the audience to the XL-1 moon lander from a guidance, navigation and control perspective.

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LET THERE BE LIGHT – MINIMIZING SOLAR ECLIPSE ON DISTANT RETROGRADE ORBIT

Yang Sun,[*] Chihang Yang,[†] and Hao Zhang[‡]

Eclipse avoidance is essential for space missions, which affects power subsystem and thermal control subsystem of spacecrafts. The eclipse situation on Distant Retrograde Orbits (DRO) is the focus of this work. A large-scale numerical searching approach is proposed to handle the problem of eclipse avoidance. The initial orbital condition is chosen near synodic resonant DROs with a large amplitude perpendicular to the Moon's orbit. A multi-objective genetic algorithm is adopted to optimize the maximum single eclipse duration and orbit stability simultaneously. Flight time and distances between the spacecraft and the Moon are constrained to prevent orbital divergence. Monte-Carlo simulations are performed to test the robustness of the results against various errors. The optimization results demonstrate that it is possible to avoid solar eclipses for a 4-year mission completely.

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AAS 21-724

MISSION DESIGN CONSIDERATIONS FOR ROBOTIC LUNAR AND GATEWAY PAYLOAD RETURN

M. M. Wittal,[*] J. D. Smith,[†] and A. M. Cassell[‡]

A selection of lunar return trajectories is examined and assessed in terms of payload mass, vehicle mass, mission time, mission complexity, and total delta-V using a range of assumptions for the mission design based on historical precedence and near-future vehicle availability. Direct surface return trajectories using a single burn solution are compared with a range of Near-Rectilinear Halo Orbit return and Ballistic Return Trajectories. This study weighs anticipated mission needs, requirements and constraints with the aim of assessing the feasibility of commercial lunar cargo and/or sample return options utilizing NASA's Gateway and Deep Space Logistics project.

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MODIFIED STATE OBSERVER FOR CHARACTERIZATION OF UNMODELED DYNAMICS IN CIS-LUNAR MISSIONS

Yrithu Thulaseedharan Pillay,* Matthew Chace,† Kyle Messick,‡ James Steck,§ and Atri Dutta**

Modified state observer (MSO) is a class of single-layer neuro-adaptive observers useful for capturing uncertainties in nonlinear systems. This paper proposes the use of MSO to capture the unmodeled perturbations acting on a spacecraft operating in cis-lunar space. The known dynamics are considered to be given by the circular-restricted three-body problem, while the true dynamics allow for the consideration of the true lunar ephemeris and other perturbations. A novel perspective is also provided on the MSO learning rule, based on optimization theory. The performance of the developed algorithm is investigated for the following mission scenarios: direct Earth to Moon transfer, low-thrust orbit-raising and halo orbits; and the effectiveness of MSO is demonstrated through numerical simulations. In this context, the selection of neural network basis functions and the tuning of MSO parameters are also discussed.

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AAS 21-739

NASA/GSFC'S FLIGHT SOFTWARE CORE FLIGHT SYSTEM IMPLEMENTATION FOR A LUNAR SURFACE IMAGING MISSION

Mohammed Eleffendi,[*] Daniel Posada,[†] M. İlhan Akbaş,[‡] and Troy Henderson[§]

The interest in returning to the Moon for research and exploration has increased as new tipping point technologies are providing the possibility to do so. One of these initiatives is the Artemis program by NASA, which plans to return humans by 2024 to the lunar surface and study water deposits in the surface. This program will also serve as a practice run to plan the logistics of sending humans to explore Mars. To return humans safely to the Moon, multiple technological advances and diverse knowledge about the nature of the lunar surface are needed. This paper will discuss the design and implementation of the flight software of EagleCam, a CubeSat camera system based on the free open-source core Flight System (cFS) architecture developed by NASA's Goddard Space Flight Center. EagleCam is a payload transported to the Moon by the Commercial Lunar Payload Services Nova-C lander developed by Intuitive Machines. The camera system will capture the first third-person view of a spacecraft performing a Moon landing and collect other scientific data such as plume interaction with the surface. The complete system is composed of the CubeSat and the deployer that will eject it. This will be the first time WiFi protocol is used on the Moon to establish a local communication network.

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ANALYSIS OF THE RELATIVE NAVIGATION PROBLEM FOR HIGHLY ECCENTRIC EARTH ORBITING SPACECRAFT OPERATING ABOVE THE GPS CONSTELLATION

Kyle Rankin,[*] Hyeongjun Park,[†] Neerav Shah,[‡] John Krizmanic,[§] and Steven Stochaj[**]

Precision formation flying in orbits above the GPS constellation creates significant constraints for navigation systems due to the limited GPS signal available at these high altitudes. Missions such as NASA's Magnetospheric MultiScale have demonstrated techniques that permit a GPS solution while above the constellation. This paper seeks to combine these techniques with the relative navigation problem to achieve solutions with sufficient accuracy to align high-precision relative navigation systems currently under development. These systems have fairly limited fields of view requiring a relatively accurate navigation solution prior to their alignment in order for the two spacecraft to find each other.

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AAS 21-773

CHANG'E 5: TRAJECTORY RECONSTRUCTION

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The China National Space Administration (CNSA) has demonstrated a strong commitment to its Chinese Lunar Exploration Program, or Chang'e Project. Building on missions to the lunar surface and the Earth-Moon L2 point, the Chang'e 5 mission in 2020 successfully returned lunar samples to Earth. While much of China's space activities are reported on through state media sources, this paper presents two efforts to reconstruct the Chang'e 5 mission: one using public domain data sources and technical experience from lunar mission design and operations, and one using a commercial optical space surveillance network and experience in space domain awareness.

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AAS 21-783

NAVIGATION DESIGN OF THE CAPSTONE MISSION NEAR NRHO INSERTION

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The upcoming Cislunar Autonomous Positioning System Technology, Operations, and Navigation Experiment (CAPSTONE) mission will serve as a pathfinder for navigation and operations in the same near rectilinear halo orbit (NRHO) that will be utilized by NASA's Lunar Gateway. CAPSTONE will arrive at the Moon via a ballistic lunar transfer, at which point an insertion maneuver is required. The final trajectory correction maneuvers, the NRHO insertion maneuver, and two cleanup maneuvers all must be performed in quick succession, which can create navigation and operational challenges. This paper reviews the navigation design for CAPSTONE through this critical period of the mission.

[View Full Paper]

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DYNAMICAL SYSTEMS

Session Chair:

Session 8: Damien Gueho, The Pennsylvania State University

AAS 21-533

IDENTIFYING THE DAMPING MATRIX OF A FLEXIBLE STRUCTURE WITH MODAL DAMPING

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

This paper derives methods to identify the damping matrix of a flexible structure with modal damping. Proportional damping as a special case of modal damping is also considered. These methods are state-space based because the damping matrices are recovered from a state-space model of the structure, which is identified from input-output measurements.

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AN EVALUATION OF THE MODAL DAMPING ASSUMPTION FOR STRUCTURAL MODELS BY SYSTEM IDENTIFICATION

Minh Q. Phan,* Dong-Huei Tseng,† Richard W. Longman,‡ and Raimondo Betti§

This paper evaluates different damping models of a flexible structure for output prediction. All three damping models are evaluated: proportional damping, modal damping, and general damping. The different damping matrices are estimated from a state-space model of the structure, which is identified from input-output measurements.

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EXPLORATION OF SPATIAL CHAOTIC ORBITS USING ISOLATING NEIGHBORHOODS*

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

Isolating blocks and isolating neighborhoods have previously been used to compute periodic and quasiperiodic orbits around the collinear libration points in the circular restricted three-body problem. Isolating neighborhoods may be used to further explore the boundary between the Lissajous and quasihalo orbits at energies where the halo orbits have bifurcated from the Lyapunov orbits. A method to compute trajectories that are forward and backward asymptotic to the libration point invariant set using very small velocity corrections is developed here. The method is then used to compute representative trajectories within this region and characterize their behavior.

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AAS 21-598

MANIFOLD COORDINATES ABOUT THE EQUILIBRIUM POINTS IN THE RESTRICTED THREE-BODY PROBLEM

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

The Restricted Three-Body Problem (R3BP) is a chaotic Hamiltonian dynamical system that has no global analytical solutions, rather, emits the special solutions: equilibrium points, periodic orbits, quasi-periodic orbits, hyperbolic manifolds. These solutions inform our understanding of the R3BP and can be coupled to form a canonical reference system as a stand-in for orbital elements–which are not well-defined across phase space in the R3BP.We present an approach to define canonical coordinates identified with quasi-periodic orbits and their hyperbolic invariant manifolds. The approach exploits normal form theory to construct appreciable neighborhoods in which coordinates can be constructed.

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AAS 21-625

USING FINITE-TIME LYAPUNOV EXPONENT MAPS FOR PLANETARY MOON-TOUR DESIGN

David Canales,* Kathleen C. Howell,† and Elena Fantino‡

The focus of the present investigation is an efficient and general design strategy for transfers between planetary moons that fulfill specific requirements. The strategy leverages Finite-Time Lyapunov Exponent (FTLE) maps within the context of the Moon-to-Moon Analytical Transfer (MMAT) scheme previously proposed by the authors. Incorporating FTLE maps with the MMAT method allows direct transfers between moons that offer a wide variety of trajectory patterns and endgames designed in the circular restricted three-body problem, such as temporary captures, transits, takeoffs and landings. The technique is applicable to several mission scenarios, most notably the design of a moon tour.

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CHARACTERISTICS AND ANALYSIS OF FAMILIES OF LOW-ENERGY BALLISTIC LUNAR TRANSFERS

Stephen T. Scheuerle* and Kathleen C. Howell†

Low-energy ballistic lunar transfers offer propellant efficient paths to the Moon in exchange for longer duration flights. These trajectories rely on the gravitational influence of the Sun to reduce maneuvers at lunar orbit insertion. Due to the sensitive nature of transfers navigating between cislunar and heliocentric space, developing ballistic lunar transfers that fulfill mission-specific constraints remains a challenge. An Earth-Moon-Sun four-body model, i.e., the bicircular restricted four-body problem (BCR4BP), is incorporated to construct end-to-end ballistic lunar transfers. Families of transfers with both fixed trans-lunar injection and lunar orbit insertion maneuver costs are examined. A methodology to assess the sensitivity of ballistic lunar transfers is evaluated to aid in expanding the launch window for these epoch dependent paths.

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VIRTUAL-REALITY-BASED ASTRODYNAMICS APPLICATIONS USING A-FRAME: A TUTORIAL

Dhathri H. Somavarapu,[*] Parker Landon,[†] Joselyn Busato,[‡] Marcus Kaiser,[§] Kaela Martin,[**] Elif Miskioğlu,[††] and Davide Guzzetti[‡‡]

This paper is a short introduction to the design and development of virtual-reality-based immersive experiences for illustration of astrodynamics concepts. Virtual reality (VR) experiences may be built for any VR capable web-browser using state-of-the-art web software technology, such as the A-Frame development framework. VR experiences based on A-Frame can also be cast to a VR head-mounted-display device directly from a VR capable web-browser. We experimented with the creation of several VR experiences to illustrate astrodynamics concepts, and selected two examples that better demonstrate the key processes for generating astrodynamics-related content in A-Frame. The first example aims to showcase a client-side implementation; the second example is based on a client and server-side technology. A short tutorial is provided to replicate both examples. The deployment of VR experiences for astrodynamics education is also demonstrated in this work by including several VR scenes developed with A-Frame within a massively open online course (MOOC) on multi-body dynamics. In a formal assessment of the MOOC, which included a question on the effectiveness of the VR experiences to their learning, 58.7% of the students indicated a positive response to the VR content. Negative responses to the VR content are attributed to the need for better context-setup for the VR experiences and not to the experiences themselves.

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AAS 21-790

QUASI-PERIODIC NEAR-RECTILINEAR HALO ORBITS IN THE CIRCULAR-ELLIPTIC RESTRICTED FOUR-BODY PROBLEM

Daniel Villegas-Pinto,* Nicola Baresi,† Slim Locoche,‡ and Daniel Hestroffer§

This paper investigates the dynamical substitutes of the Moon's synodic and side-real resonant Near-Rectilinear Halo Orbits (NRHOs) under the Circular-Elliptic Restricted Four-Body Problem formulation. This model considers that the Earth and Moon move in elliptical orbits about each other and that a third body, the Sun, moves in a circular orbit about the Earth-Moon barycenter. The resonant periodic NRHOs are replaced by two-dimensional quasi-periodic tori in this model, which better approximate the real dynamics. We present the steps and algorithms needed to compute these dynamical structures as well as their geometry in the Circular-Elliptic model.

[View Full Paper]

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TRAJECTORY DESIGN

Session Chair:

Session 9: Angela Bowes, NASA LaRC

AAS 21-561

REVISITING TRAJECTORY DESIGN WITH STK ASTROGATOR PART 2

Cody Short,[*] Linda Kay-Bunnell,[†] Doug Cather,[‡] and Nathaniel Kinzly[§]

Humankind's surrogate presence in space continues to increase year-over-year. Indeed, space missions continue to generally grow in scale and complexity as increasingly more vehicles are placed in various regimes. Large constellations of small spacecraft as well as missions in lunar and cislunar space have expanded dramatically in recent years. For all of these efforts, effective software tools to support design, analysis and operations are critical. This paper is intended to serve as the second installment in a continuing series concerning the Systems Tool Kit (STK) Astrogator capability set from AGI, an Ansys Company.

[View Full Paper]

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DIRECTLY LEVERAGING THE STATE TRANSITION MATRIX IN STK ASTROGATOR

Nathaniel Kinzly,[*] Sai Chikine,[†] John Carrico,[‡] Mike Loucks,[§] and Cody Short[**]

Trajectory design is, as the name suggests, a design problem at heart. Trajectory designers have a wide variety of tools at their disposal in order to design the best trajectory in the context of a mission. These tools include analytical frameworks such as the Circular Restricted 3-body Problem (CR3BP) that can yield a firstguess for a trajectory, objectives such as fuel usage that can be used to compare solutions, and numerical optimizers that can take a designer from a first guess to an optimal trajectory. The state transition matrix (STM) represents an analytical tool that allows trajectory designers to perform classical dynamical system stability analyses for an orbit. These analyses have applications in rendezvous and proximity operations (RPO) missions, missions in cislunar space, and a myriad of other astrodynamics contexts. This paper will highlight new STM-related capabilities and research areas within the Systems Tool Kit (STK) Astrogator capability set from AGI, an Ansys Company and give a motivating example for how these new capabilities can be useful for trajectory designers.

[View Full Paper]

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AAS 21-609

A DATA-DRIVEN NONLINEAR OPTIMAL CONTROL OF UNSTABLE FIXED POINTS

Kyosuke Sato,* Mai Bando,† and Shinji Hokamoto‡

This paper considers a data-driven optimal control of nonlinear dynamical systems based on the Koopman operator theory. A linear regression model is obtained by the Extended Dynamics Mode Decomposition (EDMD) which is a data-driven algorithm for the approximation of the Koopman operator. A linear quadratic regulator is applied to this dynamics which corresponds to nonlinear optimal control in the state-space. The results of Duffing equation and Hill three body problem demonstrate that the EDMD is able to obtain linear dynamical system and the optimal controlled trajectories exploit the manifold structure of original nonlinear dynamical system.

[View Full Paper]

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AAS 21-611

PHYSICS-INFORMED NEURAL NETWORKS FOR OPTIMAL PROXIMITY MANEUVERS WITH COLLISION AVOIDANCE AROUND ASTEROIDS

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

Exploring small planetary bodies, such as asteroids, is essential in understanding our planetary evolution and formation. For this reason, space agencies design space missions to explore these bodies. Thus, it is necessary to develop tools to compute optimal proximity maneuvers and trajectories around asteroids accurately. However, one of the main difficulties when dealing with asteroids is their irregular shapes, which can eventually lead a spacecraft to unexpected impacts if its trajectory is not designed carefully. To this end, this paper shows how it is possible to design optimal trajectories with collision avoidance around asteroids so that the spacecraft can avoid impacts with the irregular shape of an asteroid. We do so by employing the Rapidly-Explored Random Tree (RRT*) technique, which allows us to connect multiple arches of trajectory to avoid obstacles. In particular, every single optimal arch is computed via the indirect method exploiting Physics-Informed Neural Networks (PINNs). This is done by learning the Two-Point Boundary Value Problem (TPBVP) solution arising from applying the Pontryagin Minimum Principle (PMP) to the optimal control problem. The Extreme Theory of Functional Connections (X-TFC) is employed among the PINN frameworks because it analytically satisfies the boundary constraints. The proposed method is tested to design optimal trajectories around asteroids Gaspra and Bennu while avoiding impacts with their surfaces.

[View Full Paper]

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AAS 21-706

ADJOINT CONTROL TRANSFORMATION FOR MODIFIED EQUINOCTIAL ELEMENTS: AN INDIRECT APPROACH

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

Low-thrust trajectory design can be converted into boundary-value problems, which are typically challenging to solve because of a small domain of convergence and lack of knowledge about the initial costates when indirect formalism of optimal control is adopted. Many techniques have been developed to overcome the problem of guessing the initial costate values. In this work, the Adjoint Control Transformation (ACT) method is implemented when the motion of spacecraft is described using the set of Modified Equinoctial Elements (MEEs) by leveraging the costate mapping theorem. The ACT method is indirectly used to find the initial costates for the set of MEEs (MEE-ACT). The convergence robustness and efficiency of 1) the random initialization, and 2) MEE-ACT method are compared by solving low-thrust minimum-fuel trajectory optimization problems.

[View Full Paper]

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HYPERDUAL NUMBERS FOR ARBITRARY ORBIT TARGETING

Christopher Rabotin*

When designing maneuvers, one must compute the variation of the orbital characteristics of the final orbit with respect to a maneuver at the start of the transfer. These variations correspond to the partial derivatives of the destination orbital elements over the transfer arc. Most mission design software, such as STK Astrogator and NASA GMAT, compute these partial derivatives by finite differencing. This method is computationally heavy and its precision is limited to half of the precision of the computer. This paper demonstrates how to use dual number theory to compute the partial derivatives of any arbitrary orbital element with respect to the initial state of the trajectory, and paper provides a table for the variation of orbital elements with respect to Cartesian state vector, a useful reference for novel maneuver design. Validation of the dual numbers method for targeting is also detailed, with test cases and performance benchmarks between GMAT and the free software Nyx, a blazing fast astrodynamics toolkit available in Rust and Python.

[View Full Paper]

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AAS 21-742

DESIGN OF ROBUST MANEUVERS FOR THE MMX MISSION: A CHANCE-CONSTRAINT OPTIMIZATION PERSPECTIVE

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

The design of spacecraft trajectories in nonlinear dynamical systems subject to model uncertainty and disturbances is a complex and demanding task. Methods based on robust optimization consist in accounting, within the optimization process, for the possibility of having an imperfect knowledge of state and control variables. This allows to obtain a solution in which, a priori, a small amount of propellant is traded for reduced sensitivity to uncertainties and state errors, mitigating in this way the risk of partial or complete mission failure. In this manuscript, a chance-constraint optimization method is conceived and applied to design a robust impulsive approaching trajectory for a spacecraft aimed at the Martian moon Phobos. The trajectory starts at the end of the heliocentric journey from the Earth with given uncertainty on initial conditions. Spacecraft states and control are regarded as probability distributions over time while unscented transformation is used for efficient propagation of these distributions through nonlinear stochastic system dynamics. Numerical results are presented for a case study related to the future sample return mission MMX of the Japanese Aerospace Explorations Agency (JAXA).

[View Full Paper]

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AAS 21-776

SUB-OPTIMAL FAST FOURIER SERIES APPROXIMATION FOR INITIAL TRAJECTORY DESIGN

Caleb Gunsaulus,[*] Carl De Vries,[†] William Brown,[‡] Youngro Lee,[§] Madhusudan Vijayakumar,[**] and Ossama Abdelkhalik[††]

The Finite Fourier Series (FFS) Shape-Based (SB) trajectory approximation method has been used to rapidly generate initial trajectories that satisfy the dynamics, trajectory boundary conditions, and limitation on maximum thrust acceleration. The FFS SB approach solves a nonlinear programming problem (NLP) in searching for feasible trajectories. This paper extends the development of the FFS SB approach to generate sub optimal solutions. Specifically, the objective function of the NLP problem is modified to include also a measure for the time of flight. Numerical results presented in this paper show several solutions that differ from those of the original FFS SB ones. The sub-optimal trajectories generated using a time of flight minimization are shown to be physically feasible trajectories and potential candidates for direct solvers.

[View Full Paper]

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AAS 21-787

ADAPTIVE MESH REFINEMENT SCHEME FOR EFFICIENT PARAMETRIC ANALYSIS AND TRAJECTORY DESIGN

Andrea Pasquale[*] and Michèle Lavagna[†]

The exploration of dynamical structures in multibody environments is a complex and computationally demanding task. Millions of propagations are usually required to characterize small regions of the state space around either a point, an orbit, or a trajectory of interest. Even though a PC can handle such simulations, limitations associated to the computational times exist. The paper presents a flexible algorithm to cleverly explore the state space for parametric analysis, finer resolving it only in specific regions of interest. The scheme is based on a single-parameter method which refines an initial coarse mesh in case some conditions are meet. Some applicative cases are presented too.

[View Full Paper]

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ORBIT DETERMINATION

Session Chair:

Session 12: Puneet Singla, The Pennsylvania State University

KERNEL-BASED ENSEMBLE GAUSSIAN MIXTURE FILTERING FOR ORBIT DETERMINATION WITH SPARSE DATA[*]

Sehyun Yun,[†] Renato Zanetti,[‡] and Brandon A. Jones[§]

In this paper, a modified kernel-based ensemble Gaussian mixture filtering (EnGMF) is introduced to produce fast and consistent orbit determination capabilities in a sparse measurement environment. The EnGMF is based on kernel density estimation (KDE) to combine particle filters and Gaussian sum filters. This work proposes using Silverman's rule of thumb to reduce the computational burden of KDE. Equinoctial orbital elements are used to improve the accuracy of the KDE bandwidth parameter in the modified EnGMF. Through numerical simulation, the proposed implementation is compared to state-of-the-art approaches in terms of accuracy, consistency, and computational speed.

[View Full Paper]

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A SEMI-ANALYTICAL APPROACH FOR ORBIT DETERMINATION BASED ON EXTENDED KALMAN FILTER

Bryan Cazabonne,* Julie Bayard,† Maxime Journot,‡ and Paul J. Cefola§

The paper presents an open-source orbit determination application based on the Draper Semi-analytical Satellite Theory (DSST) and a recursive filter, the Extended Semi-analytical Kalman Filter (ESKF). The ESKF reconciles the conflicting goal of the DSST perturbation theory (i.e., large step size) and the Extended Kalman Filter (EKF) theory (i.e., re-initialization at each measurement epoch). Validation of the Orekit ESKF is demonstrated using both simulated data and real data from CDDIS (Crustal Dynamics Data Information System). The ESKF results are compared with those obtained by the GTDS ESKF.

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AAS 21-634

HIGHER ORDER MOMENT MATCHING FOR CONTINUOUS MANEUVER REACHABILITY SET PROPAGATION AND NONLINEAR FILTERING

Zach Hall* and Puneet Singla†

Filtering and estimation applications rely on two complementary tasks: uncertainty propagation, and measurement update. In a classical extended Kalman filter (EKF) both tasks rely on an exact minimum variance solution to approximate linearized models. Nonlinear extensions to this method such as the unscented Kalman filter (UKF) and conjugate unscented Kalman filter (CUKF) enable higher accuracy computation of the propagated prior and the posterior mean and covariance; however, these methods only compute the first two moments and assume the posterior to be Gaussian. This work presents a direct moment matching numerical procedure for maintaining higher order statistical information throughout the filtering process, and discusses applications to data-sparse satellite tracking problems.

[View Full Paper]

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AAS 21-647

ORBIT DETERMINATION VIA PHYSICS INFORMED NEURAL NETWORKS IN CISLUNAR ENVIRONMENT

Andrea Scorsoglio,* Luca Ghilardi,† and Roberto Furfaro‡

In this paper, orbit determination in the Circular Restricted Three-Body Problem (CRTBP) lunar environment is solved via Physics-Informed Neural Networks (PINNs). Extreme Learning Machines are used to estimate the state of the spacecraft along the entire observation span, abiding to the CRTBP dynamics of the cislunar space. This is possible thanks to a loss function that comprises the measurement error based on angle observations and a regularizing term based on the differential equations modeling the dynamics of the problem. This ensures that the learned relationship between input and output is compliant with the measurements and the problem's physics simultaneously. The methods show good estimation performance both in Lyapunov and halo orbits.

[View Full Paper]

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AN ALGORITHM FOR INITIAL ORBIT DETERMINATION OF UNCOOPERATIVE TARGETS USING LASER RANGING

Mark L. Psiaki,[*] John R. Bowman,[†] J. Hunter Deligne,[‡] and Trevor N. Wolf[§]

Satellite laser ranging is applied to data from objects that do not carry retro-reflectors in order to test a suite of algorithms that can perform initial orbit determination even when there are many clutter photon returns. These algorithms will enable laser ranging systems to be used for a small or distant object whose number of true photon returns is very small relative to the number of clutter photons. The suite of algorithms was proposed in a previous paper and tested using simulated data. The present paper updates the algorithm suite and tests it on real data. The algorithms fuse short arcs of cluttered laser range data with short arcs of angular data to produce initial estimates of satellite orbits. Data from an Australian observatory have been used to determine orbits when there are as many as 9,500 clutter photons and only about 50 true photons from the laser ranging system.

[View Full Paper]

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AAS 21-789

ANALYTIC INITIAL ORBIT DETERMINATION USING SATELLITE STREAKS IN DIGITAL IMAGES

John A. Christian*

Earth orbiting satellites often appear as streaks in images collected by inertially pointed cameras or telescopes. This work presents a novel method of initial orbit determination (IOD) by recognizing that such streaks define a plane tangent to the observed satellite's orbit and passing through the sensor's location. Using results from algebraic projective geometry, an analytic IOD solution may be found by solving for the disk quadric defining the 3D orbit. This solution is exact, recovering the orbit to within machine precision for two-body motion and without measurement noise. Performance in the presence of noisy measurements is also discussed.

[View Full Paper]

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ASTEROIDS AND NAVIGATION

Session Chair:

Session 13: Xiangyuan Zeng, Beijing Institute of Technology

The following paper listed in the program was not presented:

AAS 21-574

THE EVOLUTION OF DEEP SPACE NAVIGATION: 2016-2018*

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 ninth in a chronological sequence dealing with the evolution of deep space navigation. The time interval covered extends from 2016 to 2018. The paper focuses on the observational techniques that have been used to obtain navigational information, propellant-efficient means for modifying spacecraft trajectories, and the computational methods that have been employed, tracing their evolution through 12 planetary missions.

[View Full Paper]

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AAS 21-567

USING ROBUST CONTROL FOR A FAST EXPLORATION OF AN ASTEROID

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

We use nonlinear robust guidance laws to assess the possibility of an autonomous spacecraft fast approaching and orbiting an asteroid with inadequate knowledge of its properties. The spacecraft uses onboard batch-sequential filtering to navigate while making a rapid approach with the aim of orbital insertion. The end of the mission consists of the spacecraft orbiting the asteroid in a tight and naturally unstable orbit, using a robust orbital station-keeping control. We show with conservative assumptions that the proposed architecture is viable within current technology, with the adequate exploration of the body in a week. The results suggest that such an approach has tremendous impacts in terms of costs and scientific data acquisition. They also subside studies on onboard shape reconstruction, indicating that a 1σ uncertainty of 2.0% in the asteroid's shape is still viable for an autonomous safe operation.

[View Full Paper]

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APPLICATION OF GRAIL GRAVITY MODELS TO LADEE FLIGHT DATA: IMPROVEMENTS IN ORBIT DETERMINATION ACCURACIES AT THE MOON

Ryan Lebois,[*] Craig Nickel,[†] and Lisa Policastri[‡]

NASA's Lunar Atmosphere and Dust Environment Explorer (LADEE) launched from Wallops Flight Facility on September 6, 2013, two years after launch of the Gravity Recovery and Interior Laboratory (GRAIL) mission. Timing was nearly fortuitous for the LADEE operations team, but gravity models derived from GRAIL mission data were not yet available for pre-launch analysis and operations. This left the LADEE team with the task of meeting orbit accuracy requirements using a gravity model developed from the Lunar Prospector mission in 1999. This paper explores improvements achievable with current GRAIL gravity models and the implications for current and future lunar orbiters.

[View Full Paper]

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AAS 21-751

OPTIMIZATION OF MULTIPLE-GRAVITY ASSIST TRAJECTORIES TO EXPLORE ASTEROID 2010 TK7

Brian D. Kaplinger,[*] Zachary Rhodes,[†] and Frank Bonet[†]

Multiple-Gravity-Assist trajectories to visit the Earth Trojan Asteroid 2010 TK7 are developed and presented, with context support for relevant mission structures. Two classes of mission designs are summarized. The first mission design includes a primary spacecraft launch and approach to the target suitable for a Discovery or New Frontiers class program, while the second mission design assumes launch as a secondary payload suitable for the Discovery program or similar small satellite mission opportunity, such as MIDEX. Preliminary propulsion system design is conducted to demonstrate a closed mission mass budget for the proposed trajectory options.

[View Full Paper]

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AAS 21-766

THE BIRTH OF HALO ORBITS, A FIFTIETH ANNIVERSARY

David W. Dunham,[*] Ahmed Kamel,[†] David L. Richardson,[‡] Kathleen Howell,[§] and Irene Vostokova Farquhar[**]

Although Robert Farquhar, the father of halo orbits, considered them about the Earth-Moon L2 (EM-L2) libration point, to allow a satellite there to provide a lunar far-side communications capability, as early as 1959, his work until 1971 focused on Lissajous orbits, and ways to change them with maneuvers to maintain a halo geometry. The consequent total ΔV's were significant after a few years. In his doctoral thesis, Farquhar developed analytical formulae for planar halo orbits to second order. In 1970 and 1971, Farquhar and his colleague, Ah-med Kamel, expanded that work to three dimensions and 3rd-order, proving for the first time that natural 3-dimensional quasi-periodic halo orbits existed. The work was done for the Apollo program, which ended up never landing on the lunar far side, nor supporting communication for critical far-side maneuvers that were performed by each Apollo lunar mission. The history of using halo orbits for actual missions, starting with the 3rd International Sun-Earth Explorer (ISEE-3), will be described. The rich variety of libration-point missions that followed during the next half-century is described, along with promising possibilities for the future.

[View Full Paper]

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INTERPLANETARY TRAJECTORIES

Session Chair:

Session 14: Powtawche Valerino, NASA Marshall Space Flight Center

The following paper listed in the program was not presented:

AAS 21-734

AAS 21-517

LISA TRAJECTORY DESIGN

Waldemar Martens[*] and Eric Joffre[†]

The Gravitational Wave observatory, LISA, is going to be launched in 2034 and placed in a triangular cartwheel formation in an Earth leading or trailing orbit. The cartwheel orbit must be designed such that the corner angle variations remain within 60:0° ± 1:0° over 10 years. A fuel-optimal transfer to that orbit can only be achieved by optimizing the transfer and the operational cartwheel together taking the interdependence into account. Results of such an orbit design using SEP will be presented. Moreover, the question of cartwheel stability given the insertion accuracy from a full navigation analysis will be addressed.

[View Full Paper]

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RENDEZVOUS TRAJECTORIES FOR DS-OTV MISSION ON WEAK STABILITY BOUNDARY ORBITS

Roger Gutierrez Ramon,[*] Yuying Liang,[†] Yuichi Tsuda,[‡] and Yasuhiro Kawakatsu[§]

Novel designs for deep space exploration have been developed during the past years. The Deep Space Orbit Transfer Vehicle (DS-OTV) is such one, placing an OTV in a parking orbit in the Earth's vicinity used for refueling purposes for deep space missions. The possibility of rendezvous between both spacecraft is fundamental, warranting a study about it. Candidate parking orbits are systematically studied, and the usage of natural dynamics to obtain rendezvous trajectories is analyzed. Different types of orbits are characterized and evaluated on their usage feasibility taking into account flexibility, fuel usage and time taken, amongst other factors.

[View Full Paper]

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GRAVITY ASSIST MANEUVER COMBINED WITH CONTINUOUS THRUST IN THE ELLIPTICAL RESTRICTED THREE-BODY PROBLEM

A. F. S. Ferreira,* A. Elipe,† R. V. Moraes,‡ A. F. B. A. Prado,§ O. C. Winter**

The gravity assisted maneuver combined with continuous propulsion will be studied in the present paper using the elliptical restricted problem as the dynamical model. This model is important in the situations where the primary bodies are in eccentric orbits around their center of mass, like in the Sun-Mercury and Sun-Mars systems. Maps showing the energy given to the spacecraft by this combined maneuver are made, so we can evaluate better the applicability of this technique. The main objective is to find the geometries that give a better performance for this combined maneuver when compared to the situation where propulsion and gravity assisted are made separately. This combination also allows a more controlled approach to observe the celestial body.

[View Full Paper]

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A MULTI-PROBE MISSION TO MERCURY, MARS, AND VENUS

Hayden Allen*, Sam Henderson*, Thomas-Allan Tison*, Andy Wilcox,*
and James Evans Lyne†

This study examined the feasibility of a mission that would send separate probes into orbit around Mercury, Venus, and Mars. Launch would be accomplished using a single Atlas V 551, which has sufficient payload capacity for the three approximately 708 kg dry mass probes and the propellant necessary for the various propulsive maneuvers required en route. The final trajectory chosen for this mission has an optimal launch date of July 24th, 2036, with values for C3 and declination of 18.7 km^2/s^2 and 17.6°, respectively. The final encounter excess speeds for Mercury, Venus, and Mars were 2.69, 3.00, and 2.39 km/s, respectively.

[View Full Paper]

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AAS 21-693

A SURVEY OF MISSION OPPORTUNITIES TO TRANS-NEPTUNIAN OBJECTS – PART 7: UTILIZATION OF A DELTA V EARTH GRAVITY ASSIST

Colter W. Russell,[*] Christopher J. Busic,[*] Andrew M. Farris,[*] Jeongmin A. You,[*] Raj V. Patel,[*] Samantha Ramsey,[*] and James Evans Lyne[†]

The recent success of the New Horizons mission has heightened public interest and awareness of the distant, poorly-understood region of the Solar System known as the Kuiper Belt. The current study was designed to identify promising trajectories to additional targets among the thousands of trans-Neptunian objects that have now been cataloged. The objective was to maximize the potential mass on target, while maintaining reasonable values of transit time, arrival excess speed and planetary flyby distances. The approach was to combine a ΔV Earth gravity assist with a Jupiter flyby. The addition of the ΔVEGA lengthens the transit time by approximately two year but allows departure C3 values under 30 km^2/s^2, resulting for many cases in a mass on target of over 2000 kg for launch on an Atlas V 551. Promising trajectories using this architecture and departing Earth between 2029 and 2042 are presented for seven targets, including Sedna, which will reach the perihelion of its 11,400 year orbit in 2076.

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AAS 21-725

DYNAMIC PROGRAMMING APPLIED TO RESONANT FLYBY DESIGN

Giulio Campiti,[*] Alessandro Masat,[†] and Camilla Colombo[‡]

The implementation of resonant gravity assist maneuvers is an essential prerequisite for interplanetary missions requiring complex trajectory solutions. A convenient formalism to design resonant trajectories is the b-plane, as post-encounter orbits with prescribed semi-major axis can be easily mapped on this plane and thus targeted a priori. This result was originally derived in the approximation of pure circular orbits of the flyby bodies and is analytically extended in this work to account for their actual eccentricity. The classical model and the extended one are tested and compared on two mission design applications, showing non-negligible differences when the flyby body has a marked orbital eccentricity and/or the flyby takes place at one of the apsidal points. A dynamic programming approach to the design and optimization of unperturbed resonant trajectories is proposed, using as discrete decision variables a set of resonance ratios and the total number of flybys. The developed algorithm is tested by reproducing the design of Solar Orbiter's resonant phase with Venus, used in the actual mission to gradually raise the ecliptic inclination and reduce the distance at perihelion.

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AAS 21-738

COMPARISON OF LINEAR AND NONLINEAR NAVIGATION STRATEGIES FOR A EUROPA LANDER CONCEPT

Rohan Patel*† and Sonia Hernandez*‡

Navigation strategies typically use linearized techniques to predict maneuver statistics. This method has been successfully employed on numerous high-energy trajectories, but may not be valid for low-energy ones due to the highly nonlinear environment. We explore nonlinear navigation techniques applied to a Europa Lander concept by assessing trajectory sensitivity. The linearity assumption is tested at different phases of the end-game trajectory. Maneuver strategies and placement are considered to improve the delivery to Europa. Nonlinear statistical maneuver Monte Carlo simulations are conducted to optimize maneuvers and compare ΔV statistics against conventional linear simulations.

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SINGLE VEHICLE MARTIAN CYCLER TRAJECTORIES

Daniel Owen* and Brian Kaplinger†

A new Earth-Mars cycler architecture is introduced in the form E-M-ME-E. This itinerary has two short legs for human travel between the planets and two long phasing legs, one from Earth to Earth and one from Mars to Mars. Due to the two short legs the system only requires one vehicle for a round trip mission. The problem is parameterized with 3 time of flight terms and one geometric term leading to a denser solution space at the expense of higher dimensionality. A framework is developed for solving and optimizing the problem with a focus on quick interchangeability to allow for fast design and analysis.

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SATELLITE CONSTELLATIONS

Session Chair:

Session 14: Christopher Roscoe, Ten One Aerospace

AAS 21-660

CONCEPT FOR SPACE-BASED INTERFEROMETER USING FORMATION FLYING CUBESATS

Chase Pellazar,[*] Michael Corpuz,[†] and Navid Nakhjiri[‡]

Space-based interferometry is a burgeoning field in the space industry brought on by the want to perform the same radio science in more optimal conditions than that of ground-based telescope arrays. However, while this application for formation flying CubeSats is becoming popular it is still a new idea to be validated. In this paper, the conceptual design of a CubeSat interferometer array and formation design algorithm for the array are presented. Requirements are derived from a Science Traceability Matrix (STM) and trade studies are performed to assess best design choices and configurations. A Reinforcement Learning algorithm is developed with a focus on initial spacecraft formation positions while optimizing interferometer performance. This concept will be used to demonstrate the feasibility of formation flying as well as perform science in the form of interferometry.

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AAS 21-676

SATELLITE CONSTELLATION TASK PLANNING FOR INTELLIGENT REMOTE SENSING

Hao Peng[*] and Xiaoli Bai[†]

A Bayesian optimization based satellite constellation is presented for intelligent remote sensing. Conventionally, the Earth observation data is processed on the ground and the observation schedules are also planned on the ground. In the interest to have an autonomous and intelligent system onboard satellites, this paper develops a framework in which new measurements are interpreted on-board using Gaussian Process (GP) surrogate models, which in turn enables the intelligent decisions on observation targets. Challenges of using this concept to satellite constellations include potential data exchange delays and significant computational complexity. The paper provides a solution by constructing a system consisting of a global GP model for the constellation and individual GP models for each satellite. The study case is to observe the total column ozone using three satellites. Simulation results demonstrate the proposed framework increases modeling accuracy and precision compared with the classical nadir pointing method. Furthermore, the proposed modeling is effective to improve the system performance by having a global model.

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AAS 21-714

GLOBAL RECONFIGURATION OPTIONS FOR 2D LATTICE FLOWER CONSTELLATIONS AND SLOTTING ARCHITECTURES

David Arnas* **and Richard Linares†**

This work focuses on the study of the reconfiguration strategies available for uniformly distributed satellite constellations and slotting architectures. Particularly, this manuscript deals with the cases of reducing, maintaining, and also increasing the number of available positions for satellites in the space structure, and takes into account the potential minimum distances between spacecraft in the configuration to assure the safety of the system. To that end, several approaches to solve the reconfiguration problem are presented based on the properties of Flower Constellations, and more particularly, on the properties of uniformity and symmetries present in these uniform distributions.

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AAS 21-718

OPTIMAL MULTI-SPACECRAFT COOPERATIVE RENDEZVOUS AND CONSTELLATION DEPLOYMENT TRAJECTORIES

Chandrakanth Venigalla* and Daniel J. Scheeres†

This paper develops a method for solving cooperative rendezvous and deployment problems. For cooperative rendezvous, spacecraft have fixed initial orbits and the rendezvous orbit location is optimized to reduce the total fuel expended. We also explore the deployment problem as the reverse of the rendezvous problem; the final orbit is fixed and the orbit they are deployed from is optimized to reduce the total fuel expended.

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AAS 21-719

A LAGRANGIAN RELAXATION-BASED HEURISTIC APPROACH TO REGIONAL CONSTELLATION RECONFIGURATION PROBLEM

Hang Woon Lee[*] and Koki Ho[†]

A group of satellites—with either heterogeneous or homogeneous orbital characteristics and/or hardware specifications—can undertake a reconfiguration process due to variations in operations pertaining to regional coverage missions. This paper is concerned with the optimization of the specifications of the reconfiguration process that maximizes (resp., minimizes) the utility (resp., the cost). The specifications refer to the final design configuration and the transportation of satellites from one configuration to another. The utility refers to the coverage performance of the final configuration; the cost refers to the ΔV consumed or the time of flight incurred due to the reconfiguration process. We present an integer linear program formulation of the regional satellite constellation reconfiguration problem and two heuristic solution methods based on Lagrangian relaxation.

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AAS 21-728

TWO-SPACECRAFT ORBITING IN OPPOSITION TO ENABLE BISTATIC RADAR OBSERVATIONS AROUND AN ASTEROID

Sonia Hernandez,[*] Saptarshi Bandyopadhyay,[*] Mark S. Haynes,[*] Reza R. Karimi,[*] and Rodney L. Anderson[*]

Fundamental answers about the origin and evolution of the Solar System hinge on our ability to image in detail the 3D interior structure of small bodies at high-resolution. By collecting radar measurements we can ultimately create 3D maps of the interior structure. In this study we focus our attention on a specific mission scenario which consists of a carrier spacecraft and two daughter spacecraft sent to orbit the asteroid Apophis. The orbits of the spacecraft are optimized to maximize radar measurements by dynamically modeling the harmonics and solar radiation pressure. For long mission durations, orbital correction maneuvers maintain the spacecraft in formation.

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AAS 21-754

CONSTELLATION DESIGN FOR MONITORING HIGH-FREQUENCY GRAVITY SIGNALS USING GENETIC ALGORITHM

Kwonhee A. Lee* **and Brian C. Gunter†**

A Non-dominated Sorting Genetic Algorithm (NSGA)-III is used to design non-symmetric satellite constellations that can serve as a complementary system for GRACE-like missions to observe high-frequency gravity signals. The functionality of NSGA-III is first validated by reproducing optimal satellite constellations from the literature. Then, NSGA-III is used to generate 225 non-dominated constellations which are used to estimate spherical harmonics coefficients over 1 day intervals with 100 seconds sampling times. The primary measurement instrument of the constellations are optical clocks with uncertainty level assumed to be $4{:}8 \times 10^{-17} / \sqrt{\tau}$. Improvement in the absolute quality of estimated coefficients is needed but the relative quality shows that non-symmetric constellations can be more optimal than symmetric constellations in terms of gravity field modeling.

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AAS 21-756

TOWARD CO-EVOLVING SOLUTIONS OF ADVERSARIAL GROUND STATIONS TRANSIT TIME GAMES FOR P-LEO CONSTELLATION MANAGEMENT

Manuel Indaco,[*] Sean Harris,[†] Deacon Seals,[†] Daniel R. Tauritz,[‡] and Davide Guzzetti[§]

As society increasingly relies on space infrastructure for both civil and military applications, the number and the size of satellite constellations in low Earth orbit (LEO) is expected to substantially increase within the next decade; cost reduction combined with increased availability of satellite technology across different functions is granting access to space and space assets to a larger number of parties, potentially including bad actors. Malevolent actors may target both the ground and the space segment on different levels: hacking, spoofing, hijacking and command intrusion are just a few examples of the variety of attacks that can affect the performance of a constellation. In the context of different threats, the impact of an attack is greater the longer it remains undetected. Without satellite interlinks or additional in-orbit supporting networks, orbital motion is one of the primary factors contributing to the detection time for LEO assets. At the minimum, a compromised satellite has to transit from the attack location to the first available defender ground station for the attack to be detected and a mitigation action to occur. In this work, we investigate the particular problem of adversarial ground station transit time by applying coevolutionary algorithms. The solution space of adversarial ground station transit time may rapidly become intractable for analytical or brute force approaches just by the addition of a small number of satellites, orbital planes, or ground stations; thus, after defining a semi-analytical method that is able to describe the problem with one satellite and two ground stations, we apply meta-heuristic algorithms, specifically competitive coevolution, to explore adversarial ground station transit time games with increasingly higher-dimensional solution spaces. For example, coevolutionary algorithms may enable solving adversarial scenarios that include mobile attacking stations, ones that may introduce an additional layer of complexity in determining the origin and attribution of an attack. Results demonstrates how, through evolution, effective strategies for malevolent actors can be found even within scenarios whose mathematical formulation is either too difficult to develop or, if the formulation exists, does not have a closed-form solution.

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GUIDANCE, NAVIGATION, AND CONTROL

Session Chair:

Session 17: Donghoon Kim, University of Cincinnati

AN ALGEBRAIC METHOD FOR OPTIMIZING THE STATE, CONTROL, AND TERMINAL STATE WEIGHT MATRICES FOR OPTIMAL FEEDBACK CONTROL

Daegyun Choi,[*] Donghoon Kim,[†] and James D. Turner[‡]

The necessary conditions for formulating optimal feedback control algorithms have been known for many years. Free parameters exist in the performance index in the form of state and control penalty and terminal state penalty matrices for tuning the performance of the optimally controlled system. The selection process is typically experimental and iterative. To generate the weight matrices for optimal feedback control algorithms, an optimization process is proposed. Typically, the optimization process for the weight matrices requires several numerical integration processes that are computationally expensive; this work overcomes the classical high computational cost by exploiting closed-form solutions for the time-varying Riccati matrix, state trajectories, state transition matrix, and the optimal performance index. Closed-form algebraic equations are used to generate all partial derivative calculations, and no numerical integration is required. The closed-form partial derivatives are used to generate analytic gradients for the optimization steps. The optimization strategy seeks to minimize the terminal state values for the feedback control problem. A numerical example is presented to demonstrate the effectiveness of the proposed optimization algorithm. The resulting computational procedures are expected to be broadly useful for control theory applications in science and engineering.

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POINTING ALIGNMENT ESTIMATION FOR GEOSTATIONARY HIGH-RESOLUTION TELESCOPE SATELLITE BY OBSERVING STARS

Yosuke Takeo,* Takeshi Sekiguchi,* and Shinji Mitani*

The geostationary Earth observation satellite conceptual study by the Japan Aerospace eXploration Agency (JAXA) must orient its telescope precisely because of the small angle of view for one pixel. This paper proposes a method to estimate the pointing alignment of a geostationary telescope using an extended Kalman filter and reference stars. The telescope is pointed at deep space to estimate pointing alignment with high accuracy. Simulations show that the proposed method can estimate the pointing alignment without ground control points. In addition, the paper also presents a sensitivity analysis according to the characteristics of the spacecraft attitude sensor.

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AAS 21-659

UNCERTAINTY ESTIMATION THROUGH POLYNOMIAL MAP INVERSION

Simone Servadio[*] and Renato Zanetti[†]

This paper investigates the estimation of the uncertainties of a system using polynomial map inversions. The measurement noise influence on the observations from the sensors can be mapped back into the initial state probability density function. Therefore, a new technique that analyzes which portion of the 'a priori' distribution could have generated the measurements is proposed. The algorithm is tested in different applications, under either a square map and a case with measurement deficit.

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AAS 21-685

SLIDING-MODE OBSERVER-BASED NAVIGATION ALGORITHMS AND ARTIFICIAL POTENTIAL FIELDS FOR SPACE PROXIMITY OPERATIONS

Davide Celestini,* Martina Ciavola* and Elisa Capello†

This paper proposes Sliding-Mode Observer (SMO) and Artificial Potential Field (APF) as Navigation and Guidance algorithms for space applications. Both robust linear first-order and Super-Twisting SMOs are designed for performing sensor filtering measurements. Optical cameras and accelerometers are considered as sensors. A comparison with an Extended Kalman Filter (EFK) is proposed, in order to show the effectiveness of SMOs as alternative navigation algorithms. Harmonic 3D functions for the APF algorithm are proposed to manage issues related to the presence of local minima. Moreover, the repulsive field is changed for including moving targets and obstacles. Finally, the effectiveness of these algorithms is shown through numerical simulations, achieving results suitable for autonomous Rendezvous and Proximity Operations.

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AAS 21-700

A LINEAR QUADRATIC TRACKER-BASED CONTROL APPLIED TO THE SPORT NANOSATELLITE

Lara T. Oliveira,[*] Kátia M. Santos,[†] Willer G. Santos,[‡] Eduardo E. Bürger,[§] Luis E. V. L. Costa,[**] and Valdemir Carrara[‡]

This work presents a study for the application of a Linear Quadratic Tracker (LQT) control law for the attitude control of the SPORT mission's CubeSat. The aim is to computationally implement the proposed control technique in the Attitude Determination and Control Subsystem, ADCS, of the mission's satellite, then compare the results obtained with those from the current PID control. The implementation is done in Matlab, where the nonlinear equations of attitude dynamics and kinematics, sensor and actuator models, environmental disturbances, and the attitude control law are included. The LQT control satisfies the requirements of the ADCS, turning out in a more accurate pointing in the nominal and Sun pointing operation modes. However, results have indicated that the proposed control can result in a higher energy consumption in some cases.

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AAS 21-731

LINE-OF-SIGHT EXTRACTION ALGORITHM FOR DEEP-SPACE AUTONOMOUS NAVIGATION

S. A. Bella,* E. Andreis,† V. Franzese,‡ P. Panicucci,§ and F. Topputo**

The proliferation of deep-space probes is posing new challenges in navigating them with ground-in-the-loop methods. Ground tracking stations will reach saturation owing to the escalation of small satellites in deep-space. Thus, autonomous guidance, navigation, and control methods that are independent from ground communications are necessary for future deep-space satellites. For deep-space applications, planets are used as beacons to determine the observer state in deep-space using line-of-sight navigation and celestial triangulation. This paper introduces a planets line-of-sight extraction algorithm for deep-space autonomous navigation. In particular, the methodology focuses on image generation, image processing, and line-of-sight extraction. The probe attitude is estimated from generated images and, if a planet is detected, its line-of-sight is extracted to enable the autonomous satellite position estimation. Numerical simulations show that a 3σ accuracy of 20 arcseconds for the planet line-of-sight can be reached, yielding to a 3σ accuracy of 1000 km for autonomous position estimation during deep-space application.

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AAS 21-762

SENSITIVITY ANALYSIS OF ADAPTIVE GUIDANCE VIA DEEP REINFORCEMENT LEARNING FOR UNCOOPERATIVE SPACE OBJECTS IMAGING

Andrea Brandonisio[*] and Michèle Lavagna[†]

In this work a Proximal Policy Optimization (PPO) algorithm is explored to setup an agent that, via imaging, plans sub-optimal paths to fly-around an uncooperative and unknown orbiting object with shape reconstruction purposes. The proximity dynamics between the spacecraft and the target object of the chaser agent is linearized taking into account the target orbital eccentricity; rotation of the target object is included only. The target geometry is rendered as a polyhedron shaped model with a triangular mesh. The PPO algorithms is deeply analysed to improve the stability and reduce the sensitivity of the algorithm with respect to the particular conditions in which the problem is solved. Both policy and state-value functions are approximated using Artificial Neural Networks (ANN) and trained according to RL principles. To improve the stability and robustness of the agent in different scenario conditions, a formulation exploiting recurrent layers is proposed and studied. Random initial environment conditions are adopted to train the agent to react to largely different operational scenarios. A large database of training tests has been collected, exploiting the network configurations already designed in our previous work. The proposed method and its results are critically presented to contribute to the RL techniques applicability in the field of proximity guidance synthesis for image based chasers fly-around uncooperative objects, possibly expanding the baseline research for future works on autonomous guidance in space engineering.

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A NOVEL PARTICLE SWARM OPTIMIZATION ALGORITHM FOR CONTINUOUSLY MEASURABLE ENVIRONMENTS (CMPSO)

Gregory Hatfield,* Thomas Fuller,* Kyle Sanders,* and May-Win L. Thein†

Implementation of the Particle Swarm Optimization (PSO) algorithm thus far has focused primarily on PSO development and implementation in simulation and with less consideration for experimental field testing. In recent works at the University of New Hampshire, combinatorial optimization was used to improve the efficiency of PSO on a swarm of Unmanned Ground Vehicles (UGVs) by the development of a Transcending PSO (TPSO) algorithm for use in extraterrestrial resource prospecting. However, similar to standard PSO, TPSO samples fitness scores only once, at the beginning of each discrete iteration. For scenarios where continuous fitness measurement is possible (i.e. electromagnetic prospecting) during navigation to the designated iteration waypoint, significantly more information may be gleaned and, in turn, provided to the swarm by this type of mid-iteration fitness sampling. In this paper, the authors propose the Continuous Measurement Particle Swarm Optimization (CMPSO), a novel implementation of the PSO algorithm using continuous fitness sampling. The proposed modification of PSO (and TPSO) is designed to significantly improve efficiency and efficacy of optimized search missions with only marginally increased computational complexity. In this paper, the CMPSO algorithm is compared that of to the standard PSO algorithm and an Adjusting CMPSO (ACMPSO) algorithm with retroactive position and velocity adjustment. Analytical and experimental results found both continuous variants yield greater performance and efficiency across six different metrics. The ACMPSO variant yields significantly greater efficiency compared to the non-adjusting version, but is less robust when utilized with lower swarm populations.

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AAS 21-779

DESIGN OF LQR WEIGHTING MATRICES FOR TIME VARYING OUTPUT COVARIANCE ASSIGNMENT

Vishala Arya,[*] Raman Goyal,[†] Manoranjan Majji,[‡] and John L. Junkins[§]

A time-varying output covariance assignment problem in the presence of a stochastic disturbance is solved using finite-horizon optimal control formulation. It is shown that an assignment of time-varying output error covariance is possible in the presence of model error by utilizing a time varying linear quadratic regulator (LQR) controller with a class of output and control weighting sequences. The paper develops a systematic algorithm to calculate the sequence of such time varying output weights which are further shown to be the Lagrange multipliers associated with the covariance constraints. A short horizon attitude control problem with stringent covariance constraints is solved to demonstrate the utility of the proposed approach. Numerical results offer a degree of optimism about the broad applicability of the time varying covariance assignment approach to solve guidance and control problems associated with nonlinear dynamical systems.

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MARTIAN MOONS AND SOLAR SAILS

Session Chair:

Session 19: Jacopo Villa, University of Colorado Boulder

AAS 21-526

SENSITIVITY OF SOLAR SAILING PERFORMANCE TO ATTITUDE-ORBIT INTERACTION DURING THE LIGHTSAIL 2 MISSION

Maximilien Berthet[*] and Kojiro Suzuki[†]

LightSail® 2 (LS2) is the first LEO solar sailing mission with active attitude control. By varying the sunlit sail area over each orbit, LS2 has been able to regulate its semi-major axis. However, solar sailing performance has been reduced by attitude inaccuracy. Using the LS2 mission as a case study, this paper investigates the impact of pointing error on the performance of solar sailcraft in LEO, via a high-fidelity orbit-attitude simulator combined with statistical analysis. The results show that even small changes in attitude accuracy can make the difference between orbit raising and accelerated orbital decay.

[View Full Paper]

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AAS 21-559

TRAJECTORY OPTIMIZATION AND CONTROL APPLIED TO LANDING MANEUVERS ON PHOBOS FROM MARS-PHOBOS DISTANT RETROGRADE ORBITS

Vittorio Baraldi[*] and Davide Conte[†]

This paper presents research on the application of trajectory design, optimization and control to an orbital transfer from a Mars-Phobos Distant Retrograde Orbit (DRO) to the surface of Phobos. Given a DRO and a landing location on the surface of Phobos, landing trajectories for which total Δv for a direct 2-burn maneuver is minimized are computed. This is accomplished through the use of Particle Swarm Optimization (PSO) in which the required Δv and time of flight are optimization parameters. The nonuniform gravitational environment of Phobos is considered in the computation. Results show how direct transfers can be achieved with low Δv, specifically in the order of ~30 m/s.

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DESIGN OF SOLAR SAILING TRAJECTORIES RESILIENT TO SAFE MODE EVENTS

Ari Rubinsztejn,[*] Carrie Grace Sandel,[*] James B. Pezent,[*] Rohan Sood,[*] Frank E. Laipert,[†] Andrew Heaton,[‡] and Les Johnson[§]

Solar sails are an enabling technology for stand-alone small-satellite deep-space exploration. However, their always-on nature, combined with the time of flight required for deep-space missions, makes them particularly susceptible to safe mode events. Unlike missions using electric propulsion, exclusively solar sailing missions cannot carry extra propellant to make up for a safe mode event, and more powerful methods like expected availability cannot be directly applied. This work extends the expected availability and duty cycle approaches to solar sailing. Through an application to NASA's Solar Cruiser mission, a 46 % increase in trajectory resilience is obtained at negligible change in the mission's time of flight. Additionally, it is shown that when a safe mode event stops the spacecraft from reaching its target orbit, the developed methods reduce the expected final error by approximately an order of magnitude.

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AAS 21-650

HEURISTIC OPTIMIZATION APPLIED TO DISTANT RETROGRADE ORBITS AND A PRELIMINARY INVESTIGATION OF LOW-PLANETARY ORBITAL TRANSFERS

Amber Scarbrough* and Davide Conte†

This paper studies the fundamentals of the Particle Swarm Optimization (PSO) technique applied to a Distant Retrograde Orbit (DRO) around Phobos is considered. PSO is applied to find various DRO orbital amplitudes within the Mars-Phobos system to investigate the potential use of an orbital transfer from Low-Martin Orbit (LMO) to the resultant DRO. Δv is minimized to keep Time-of-Flight (TOF) within a given constraint for investigation of a direct two-burn maneuver. Results give the potential candidate of the required initial velocity and the orbital period of the desired DRO. Numerical results are then compared to existing literature for validation.

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AAS 21-778

HYBRID SOLAR SAILING AND ELECTRIC PROPULSION: A MISSION CONCEPT TO COMET 45P

Daniel Miller,* Jacob Englander,† and Richard Linares‡

While solar electric propulsion (SEP) is highly efficient, propellant requirements nevertheless reduce the mass fraction reserved for a scientific payload. Solar sails offer a propellant-free alternative, but their limited thrust results in longer transfer times. By combining solar sailing and SEP in a single hybrid spacecraft, a compromise may be reached that features both lower propellant costs than SEP and shorter times of flight than solar sailing alone. A sample mission to Comet 45P is used to explore how hybrid propulsion gives mission designers increased flexibility to balance flight times and delivered mass.

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ORBITAL DYNAMICS, PERTURBATIONS, AND STABILITY

Session Chairs:

Session 18: Brian Gunter, Georgia Institute of Technology

Session 22: Spencer Boone, University of Colorado Boulder

The following papers listed in the program were not presented:

AAS 21-666

AAS 21-696

AAS 21-529

LAGRANGIAN DERIVATION AND STABILITY ANALYSIS OF MULTI-BODY GRAVITATIONAL DYNAMICAL MODELS WITH APPLICATION TO CISLUNAR PERIODIC ORBIT PROPAGATION

Adam P. Wilmer[*] and Robert A. Bettinger[†]

With the application of assumptions restricting the orbital shape and relative inclination of celestial bodies such as the Earth and Moon, numerical analysis of the motion of small bodies of comparatively negligible mass (i.e., a satellite) within a multi-body gravitational system is possible. A particularly interesting study is the dynamical evolution from the circular restricted three-body problem (CR3BP) to higher fidelity models. In this research, Lagrangian analytical methods are applied to formulate succinct derivations of the circular restricted three-body problem, the elliptical restricted three-body problem (ER3BP) and, finally, the bicircular restricted four-body problem (BCR4BP). The synodic reference frame is implemented for all dynamical models using non-dimensional canonical units. The presence of, or lack thereof, equilibrium points within each dynamical model is discussed and presented in both graphical and tabular form. In terms of application, a form of periodic trajectories within multi-body dynamical systems (such as the CR3BP), identified herein as cislunar periodic orbits are propagated using each of the presented dynamical models. The dynamical variations in these periodic orbits when transitioning between dynamical models are analyzed and discussed with plots presented.

[View Full Paper]

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AAS 21-546

SEMIANALYTICAL MEASURES OF NONLINEARITY BASED ON TENSOR EIGENPAIRS

Erica L. Jenson[*] and Daniel J. Scheeres[†]

This paper proposes a semianalytical measure of nonlinearity (MoN) based on tensor eigenpairs. Approximating nonlinear dynamics via local linearization is a common practice that is used to enable analytical methods in dynamics, control, navigation, and uncertainty propagation. However, these linear approximations are only reasonable near the linearization point, and the size and characteristics of the linear region are dependent on the system's underlying degree of nonlinearity. MoN can be used to quantify nonlinearity, identify directions of strong nonlinearity, and predict the size of a linear region. This paper presents a novel MoN that is based on the eigenpairs of tensors that are derived from the higher-order terms in in a Taylor series expansion, e.g., the local dynamics tensors and state transition tensors. Unlike existing MoN, the tensor eigenpair measure of nonlinearity (TEMoN) is semianalytical and its computation does not require empirical sampling or numerical optimization. The TEMoN determines the direction of maximum nonlinearity and can distinguish higher-order contributions to nonlinearity. This method will be demonstrated for equilibrium points and near-rectilinear halo orbits in the circular restricted three body problem.

[View Full Paper]

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AAS 21-583

MODELLING INTERNAL STRUCTURE OF ASTEROIDS VIA DATA-DRIVEN APPROACH

Yuying Liang,[*] Naoya Ozaki,[†] Yasuhiro Kawakatsu,[‡] and Masaki Fujimoto[§]

In this work, the internal structure of an asteroid is predicted via a data-driven approach called invertible neural network (INN) using the position and velocity state observation of a spacecraft flying around it. This INN approach is especially powerful dealing with gray box problem with unmatched dimension of input and output variables. Then, targeting at heterogenous density distribution of an irregular-shaped asteroid, a multiple-layered model is proposed to approximate its internal structure. In this work, the major structure is modelled by an ellipsoid with its potential estimated by Ferrer's bar model. The mapping between the internal structure of a small body and the flying state observation of a spacecraft around it is built up numerically by INNs on sufficient tests. The prediction performances are then examined by the loss in each input and by comparing the distributions of ground truth and experimental results.

[View Full Paper]

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AAS 21-597

LOITERING OF BREAKUP EVENT DEBRIS NEAR NOMINAL GNSS ORBITS

Marielle M. Pellegrino,[*] Daniel J. Scheeres,[†] and Brett J. Streetman[‡]

This paper investigates how debris from a breakup event in medium Earth orbit will impact nominal orbits of the regime. It will examine two cases, an explosion event and a collision event, in three regimes of medium Earth orbit, GPS, Galileo, and GLONASS. Through 200 year simulations the research will show how long debris loiters near each of the nominal orbits. This region is of particular interest because luni-solar resonances cause known eccentricity growth at these semi-major axes. This work will show how that resonance structure will interact with a breakup fragment cloud and therefore how the objects will interact with neighboring regions over long timescales.

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1:1 RESONANCE CAPTURE OF A LOW-THRUST SPACECRAFT AROUND VESTA

Wail Boumchita* and Jinglang Feng†

Vesta is the second largest celestial object of the main asteroid belt and it was visited and studied by the DAWN mission in 2011. The spacecraft used solar-electric propulsion that generates continuous low-thrust. As the spacecraft slowly descends from high altitude mission orbit (HAMO) to low altitude mission orbit (LAMO), it crosses the 1:1 resonance, putting the spacecraft at risk of being permanently trapped at this altitude. The objective of this paper is to analyze the probability that the spacecraft has to be captured into the 1:1 resonance with Vesta. Firstly, we model the dynamics considering the irregular gravitational field up to the fourth order and degree and the thrust constant in magnitude and opposite to the velocity direction of the spacecraft. Then, we calculate the probability of capture for orbits with different combinations of semi-major axis and true anomaly. In addition, we simplify the dynamical model by considering the harmonic terms related to the 1:1 resonance and the second order degree harmonics, respectively. It is found that the simplified models are not capable of estimating this probability promisingly. Therefore, through pure numerical simulations of the complete model, we investigate the sensitivity of this capture to different orbital geometries and physical properties of the spacecraft. The results show that the probability of capture is more dependent on the value of the mass of the spacecraft and the magnitude of the thrust, and is less dependent on the value of the specific impulse. In addition, it is found that the spacecraft is more prone to be captured into the 2:3 resonance with Vesta if the descent starts from a non-polar orbit.

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COMPUTATION AND ANALYSIS OF JUPITER-EUROPA AND JUPITER-GANYMEDE RESONANT ORBITS IN THE PLANAR CONCENTRIC CIRCULAR RESTRICTED 4-BODY PROBLEM*

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

Many unstable periodic orbits of the planar circular restricted 3-body problem (PCRTBP) persist as invariant tori when a periodic forcing is added to the equations of motion. In this study, we compute tori corresponding to exterior Jupiter-Europa and interior Jupiter-Ganymede PCRTBP resonant periodic orbits in a concentric circular restricted 4-body problem (CCR4BP). Motivated by the 2:1 Laplace resonance between Europa and Ganymede's orbits, we then attempt the continuation of a Jupiter-Europa 3:4 resonant orbit from the CCR4BP into the Jupiter-Ganymede PCRTBP. We strongly believe that the resulting dynamical object is a KAM torus lying near but not on the 3:2 Jupiter-Ganymede resonance.

[View Full Paper]

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ADAPTIVE GAUSSIAN MIXTURE MODEL FOR TIAN-QIN CONFIGURATION UNCERTAINTY PROPAGATION

Xingyu Zhou,* Xiangyu Li,† and Dong Qiao‡

Tian-Qin is a recently proposal for a space-based detector aimed at detecting gravitational waves at low frequencies. Tian-Qin project depend crucially on the stability of the orbit and the configuration. To keep the arm-lengths, sub-tended angles, and the relative velocities acceptable, uncertainty propagation is to investigated. In this paper, a novel adaptive Gaussian mixture model method is proposed for uncertainty propagation of Tian-Qin configuration. The Gaussian mixture model is utilized for representing the orbit uncertainty of each spacecraft and the configuration uncertainty is obtained using fifth-order Cubature rule based nonlinear transformation. Simulation shows that the proposed AGMM could better represent the true distribution comparing with the fifth-order CR.

[View Full Paper]

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AAS 21-677

CHARACTERIZATION OF BALLISTIC CAPTURE CORRIDORS AIMING AT AUTONOMOUS BALLISTIC CAPTURE AT MARS

Gianmario Merisio[*] and Francesco Topputo[†]

Current deep-space missions heavily count on ground-based operations. Although reliable, ground slots will saturate soon, so hampering the current momentum in space exploration. EXTREMA, a project awarded an ERC Consolidator Grant in 2019, enables self-driving spacecraft, challenging the current paradigm and aiming, among others, at autonomously engineering ballistic capture. This work presents the characterization of ballistic capture corridors, time-varying manifolds that support capture. A preliminary methodology to approximate such entities is proposed. Results show that a mapping between corridor states and capture set initial conditions is attainable. This is a first effort in the development of an on-board autonomous ballistic capture algorithm suitable for spacecraft with limited control authority and on-board resources like CubeSats.

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AAS 21-681

CONVERGENCE BASIN ANALYSIS FOR SPACECRAFT TRAJECTORY TARGETING

Collin E. York,* Kathleen C. Howell,† and Belinda Marchand‡

One robustness measure in trajectory targeting is the ability to determine feasible trajectories under dispersions. If sufficiently large dispersions cannot be accommodated, unpredictable targeting behavior may result. Dynamical properties of the reference path and the targeting problem formulation influence the region of perturbations for which a targeting strategy reliably produces a feasible reference trajectory, denoted the convergence basin. Characterization of this basin is explored in the Circular Restricted Three-Body Problem and a higher-fidelity model. A basin metric produced from 1^{st}- and 2^{nd}-order state transition tensors evaluated on the reference path is introduced, and the correlation with discretized approaches is summarized.

[View Full Paper]

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SEARCHING FOR δV-PERIODIC ORBITS

A. F. S. Ferreira,[*] R. V. Moraes,[†] O. C. Winter,[‡] A. Elipe,[§] and A. F. B. A. Prado[**]

This study has the goal of searching for initial conditions and an impulse δV that result in δV-periodic orbits for a spacecraft around small celestial bodies. Due to the weak gravity field of the central body, the spacecraft suffers strong disturbance from the solar radiation pressure, so periodic orbits are very rare. The pro-posed method focuses on finding periodic orbits using an approximate mathematical model and, after including the solar radiation pressure, search for δV-periodic orbits that can be used to observe the celestial body, starting from the initial conditions of the previous orbit. Those orbits are artificial periodic orbits and help to increase the number of options of orbits to observe the body.

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DYNAMICS NEAR THE THREE-BODY LIBRATION POINTS VIA THE KOOPMAN OPERATOR THEORY

Simone Servadio,* David Arnas,† and Richard Linares‡

This paper investigates the application of the Koopman Operator (KO) theory to the motion of a satellite about a libration point in the circular Restricted Three-Body Problem (RTBP). Recently, the KO has emerged as a promising alternative to the geometric prospective provided by Poincaré, where the KO formulates the analysis and dynamical systems in terms of observables. This paper explores the use of KO for computing both 2D and 3D periodic orbits near libration points. Further, simulation results are included that show that the KO provides analytical solutions with high accuracy for both Lyapunov and Halo orbits.

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DIRECTIONAL STATE TRANSITION TENSORS FOR CAPTURING DOMINANT NONLINEAR DYNAMICAL EFFECTS

Spencer Boone[*] and Jay McMahon[†]

Higher-order methods such as state transition tensors (STTs) have shown promise for a variety of uses in astrodynamics, but can be limited in their use due to their potentially large computational and storage requirements. In this paper we present a method for approximating STTs by aligning the STTs with particularly unstable directions. This strategy allows us to isolate the most important terms in the higher-order STTs and ignore any less important terms. This method is shown to produce similar results to the full STTs, but requires significantly fewer terms. The method is applied to several examples for both nonlinear state and state uncertainty propagation in two and three-body dynamical systems. The method is promising for expanding the use of STTs to situations with highly nonlinear dynamics but limited computational resources, such as on-board a spacecraft.

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AAS 21-749

GRAVITATIONAL ORBIT-ATTITUDE PERTURBATIONS FOR ANY DEGREE AND ORDER POTENTIAL MODELS

Brennan S. McCann[*] and Morad Nazari[†]

In this paper, the effects of celestial bodies' nonuniform gravitational fields expressed using spherical harmonics of any degree and order on the motion of a rigid body in those fields are analytically derived and implemented for dynamic systems modeling and simulation. The rigid body dynamics are propagated in the geometric mechanics framework to account for roto-translational coupling and coupled higher order gravitational perturbations derived from the generalized spherical harmonic expansion of any degree and order. The results of this study are applied to the case of a rigid-body spacecraft motion in a lunar orbit and illustrate that higher order terms contribute non-negligible pose errors that should be accounted for in scientific missions.

[View Full Paper]

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A COMPARISON OF THE CIRCULAR RESTRICTED THREE-BODY PROBLEM AND THE BI-CIRCULAR BI-PLANAR FOUR BODY PROBLEM

Allan Kardec de Almeida Junior[*] and Antonio Fernando Bertachini de Almeida Prado[†]

The bi-planar bi-circular four body problem is compared with the circular restricted three body problem in this paper. A perturbation due to the presence of the Sun is evaluated both analytically and numerically. This perturbation shows the influence of the Sun over a satellite as a function of its position and the geometrical configuration of the main bodies. The results show that the influence of the Sun is very asymmetric on the surface of the Earth, and the map of perturbation can be used to analyze the fuel costs for space travels.

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AAS 21-764

ON THE SYMPLECTICITY OF THE STATE TRANSITION MATRIX IN DIFFERENT COORDINATES

David M. Ciliberto,* Joseph T. A. Peterson,† and Manoranjan Majji‡

A method is developed to determine under what conditions the state transition matrix is symplectic for various choices of minimal coordinate representations. It is shown that the state transition matrix for discrete conservative systems is symplectic in inertial cartesian coordinates and their derivatives, as well as for all choices of canonical variables. It is shown that the state transition matrix is not symplectic in cartesian coordinates of a non-inertial basis. A modified gyroscopic symplectic condition is then presented which does hold for cartesian coordinates in a non-inertial basis and which can be used to quickly obtain the inverse of the state transition matrix and to verify its numerical accuracy. This gyroscopic symplectic condition is then verified analytically for the Clohessy-Wiltshire Equations for relative satellite motion, as well as numerically for the circular restricted three-body problem.

[View Full Paper]

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ATTITUDE DYNAMICS AND CONTROL

Session Chairs:

Session 23: Diane Davis, a.i. solutions, Inc.

AAS 21-515

MODIFIED NONLINEAR MORSE-LYAPUNOV ATTITUDE CONTROL

Eric A. Butcher[*] and Mohammad Maadani[†]

A modification to standard Morse-Lyapunov attitude control laws on $SO(2)$ and $SO(3)$ is proposed for obtaining faster closed-loop response for initial conditions near the unstable equilibria at 180 deg principal angle where the standard control laws are known to result in poor response speed. The advantages of Morse-Lyapunov control, which eliminates both the unwinding phenomenon and the undesirable effects of discontinuous control, are first reviewed. Subsequently additional nonlinear feedback in terms of the rotation matrix is obtained and the Lyapunov approach is used to prove almost global asymptotic stability. Finally, a similar modification to quaternion-based control laws is suggested to obtain the same benefit of faster response for initial conditions near 180 deg rotation.

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AAS 21-527

CONSTRAINED ATTITUDE MANEUVERING VIA MODIFIED RODRIGUES PARAMETERS - BASED MOTION PLANNING ALGORITHMS

R. Calaon* and H. Schaub†

The attitude dynamics and control of a spacecraft become complex in the presence of constraints in its orientation. Such constraints consist in not pointing sensitive payload towards bright objects in space or, vice versa, keeping the same bright objects within some instrument's field of view. This paper investigates the applicability of motion planning algorithms to navigate a 3D grid in the Modified Rodrigues Parameters (MRPs) configuration space. The aim is to compute a feasible, constraint-compliant reference trajectory in MRP space that can be tracked to reorient a spacecraft from an initial attitude to a final attitude while also attempting at minimizing the required control effort. The path is constructed with B-Spline curves that pass through each attitude way points. Simulations show that constraint-compliant, control torque minimizing paths are found if the grid spacing is chosen to be fine enough.

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AAS 21-530

APPLIED REACHABILITY ANALYSIS AND LINEARIZED OPTIMAL CONTROL POLICY FOR TIME-OPTIMAL SPACECRAFT ATTITUDE REORIENTATIONS

Layne C. Barrett[*] and Costantinos Zagaris[†]

Satellite attitude reorientation has been of significant interest in the field of astronautical engineering, and being able to reorient in a time-optimal manner has been of exceeding interest since the 1970s. Satellite reorientations are used for a variety of mission sets, including on-orbit servicing and sensor pointing. Ensuring a mission set can be conducted within a certain amount of time raises the question of whether or not a certain maneuver can be completed with a bounded control. This paper answers that question by using the concept of reachability to provide reachable sets for different spacecraft scenarios. The reachable sets generated provide a range of initial states that guarantee a satellite will reach a desired end orientation given a certain time constraint. Being able to validate that a certain end state can be reached before a maneuver is attempted can save both time and energy expended by a spacecraft. Prior research providing a formal approach of applying reachability to spacecraft attitude maneuvers has not been found. The analysis of the reachable sets yields the insight that using Modified Rodriguez Parameters (MRPs) to generate reachable sets is computationally more efficient than other attitude parameterizations. It was also found that the linearized MRP dynamics provide a valid time optimal solution for the nonlinear dynamics of medium angle attitude maneuvers. This linearized version of the dynamics was used to formulate an optimal control policy for spacecraft reorientations with bounded controls.

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AAS 21-532

DESIGNING STEADY-STATE FILTERS FOR THE FINITE-TIME SIGNAL IN ITERATIVE LEARNING CONTROL

Tianyi Zhang[*] and Richard W. Longman[†]

Iterative Learning Control (ILC) initially aims for zero-error tracking a repeated finite-time trajectory, adjusting the command to a digital control system each run based on previous run error. Two difficulties arise. The unique zero-tracking error solution often is an unstable command. Also, ILC asks for zero error up to Nyquist frequency. Thus, robustness to high frequency model errors is required. A typical solution to both issues is to use a zero-phase low-pass filter given by the Filtfilt command in MATLAB to cutoff frequencies. This creates a mismatch in the ILC design process: the filter is designed based on frequency thinking, which is steady-state frequency response, but it is applied to finite-time signals for iteration in ILC. This mismatch can be addressed by the steady-state filters, like the Circulant Filter and the Cliff Filter, for the finite-time signal. Both filters eliminate the transients produced by the typical filters. But, both filters present issues of the Gibbs phenomenon that appears if the signal's start and end points are not equal, which is nearly always the case during ILC iterations. This reduces the tracking accuracy and convergence rate of ILC. Two approaches, single reflection and double reflection, are studied here. One is to do an even reflection about the endpoint of the signal, filter the extended signal, and then use the first half of the resulting signal. The second approach does an odd reflection about the endpoint of the original signal, then does an even reflection of this odd-reflected signal, then uses the first one fourth of the filtered signal. This is done to not only have continuity across the endpoints of the extended signal, eliminating the discontinuity at the end-points, but to maintain continuity of the first derivative of the signal. A math proof is provided to show that both methods can reduce Gibbs phenomenon, and also provides a formula indicating when it is important to use single/double reflection on signals with different start and end points. Simulation results show that both reflection methods can reduce the tracking error of ILC.

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AAS 21-551

ON DESIGNING FINITE TIME ITERATIVE LEARNING CONTROL BASED ON STEADY STATE FREQUENCY RESPONSE

Shuo Liu,[*] Richard W. Longman,[†] and Benjamas Panomruttanarug[‡]

Iterative Learning Control (ILC) is useful in spacecraft application for repeated high precision scanning maneuvers. Repetitive Control (RC) produces effective active vibration isolation based on steady state frequency response. This paper considers the finite time ILC problem addressed using steady state frequency response, comparing two methods recently developed. One adapts for ILC the FIR filter design in RC that mimics the system's steady state frequency response inverse, creating a filter designed for all frequencies from zero to Nyquist. Adjustment of gains near the beginning of the matrix need to be made because FIR gains are truncated there. The other approach uses a circulant matrix obtained from the Toeplitz matrix of Markov parameters. It is shown to give steady state frequency response for the discrete frequencies that can be seen in the number of time steps in the ILC tracking problem, but not for intermediate frequencies. The main aim of the paper is to compare the performance of each approach, and compare the ease of use. The inverse of the frequency response is used in RC to avoid the usually unstable inverse of the discrete time transfer function. Here the use in ILC has the same property, but must also eliminate error during the initial transient phase. The performance and the robustness to model parameter error do not seem to have any significant difference. Both methods can work well converging to zero tracking error. The main distinction is that the adjustment by steepest descent of a small number of gains in the Learning Gain Matrix is easier done in the FIR approach.

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AAS 21-556

DEVELOPMENT OF A NEW FAMILY OF STABLE INVERSES THAT ADDRESS CHOICES OF INITIAL AND FINAL CONDITIONS

Xiaoqiang Ji[*] and Richard W. Longman[†]

When the input to a linear differential equation model comes through a zero order hold, and the output is synchronously sampled, there is a linear difference equation whose solution is identical to that of the differential equation at the sample times. When the transfer function of the differential equation has pole excess of 3 or more, the discretization process using reasonable sample rates introduces one or more zeros outside the unit circle in the discrete time z-transfer function. The inverse problem of finding what input produces a desired output at each sample time results in an unstable input. A body of literature has appeared to allow one to have a stable input if one compromises in various ways in the statement of the desired output. This paper develops a series of solutions to four different inverse problem statements that more closely match inverses of relevant physical problems. A time shifted inverse matrix is used that: (1) Allows one to obtain a stable inverse solution for any desired initial conditions. (2) That avoids the theoretical task of solving a difference equation forward in time starting at minus infinity. And solving another difference equation backward in time starting at plus infinity. In order to determine the inverse input at each time step. (3) And it allows one to specify nonzero final conditions to reach at the end of the desired trajectory, or to reach a final condition and stay there after the end of the trajectory.

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AIDING COARSE ATTITUDE WITH IMAGE-BASED THREE-AXIS ATTITUDE MEASUREMENTS USING MULTIPLICATIVE EXTENDED KALMAN FILTER FOR SMALL SATELLITES

M. B. Güzel,* H. E. Söken,† and Ozan Tekinalp‡

Equipment and budget limitations of satellite missions encourage researchers to use onboard equipment for multiple tasks. Camera stands out as an ideal equipment that can be used for multiple purposes in satellites making Earth observation. In this study, an attitude estimation algorithm is designed to aid the coarse attitude estimates with the attitude information obtained from Earth images. Attitude information is extracted from Earth images according to perspective geometry laws. This estimated attitude is fed into a multiplicative extended Kalman filter (MEKF). Coarse attitude information is obtained by pre-processing magnetometer and sun sensor measurements within the QUEST algorithm and also used in the measurement update process of the filter to ensure the sustainability of the attitude estimates. The algorithm is tested for a hypothetical small satellite in different scenarios depending on the availability of Earth images at different times.

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AAS 21-727

AN IMPROVED PARTICLE SWARM OPTIMIZATION APPROACH FOR STATIC ATTITUDE ESTIMATION FROM LIGHT INTENSITY MEASUREMENTS

Stephen R. Gagnon* **and John L. Crassidis†**

This paper presents a modification to the standard particle swarm optimization (PSO) algorithm that improves the frequency of convergence over the standard PSO for attitude optimization. The proposed modifications leverage attitude kinematics to improve the particle update equations and generate physically motivated particle motions through the attitude space. The improved algorithm is applied to the problem of attitude determination from multi-observer light-intensity measurements, and performance is compared to the standard PSO algorithm as well as several other optimization algorithms. Good results are achieved that may also provide some insight into the nature of the multi-observer light-intensity measurement problem.

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ATMOSPHERE AND AEROCAPTURE

Session Chairs:

Session 25: Piyush Mehta, West Virginia University

AAS 21-558

SATELLITE DRAG COEFFICIENT MODELING AND ORBIT UNCERTAINTY QUANTIFICATION USING STOCHASTIC MACHINE LEARNING TECHNIQUES

Smriti Nandan Paul,[*] Logan Sheridan,[†] Piyush Mehta,[‡] and S. Huzurbazar[§]

The rapidly increasing congestion in the low Earth environment makes the modeling of uncertainty in atmospheric drag force a critical task, affecting space situational awareness (SSA) activities like the probability of collision estimation. A key element in atmospheric drag modeling is the assessment of uncertainty in the atmospheric drag coefficient estimate. While atmospheric drag coefficients for space objects with known characteristics can be computed numerically, they suffer from large computational costs for practical applications. In this work, we use cost-effective data-driven stochastic methods for modeling the drag coefficients of objects in the low Earth orbit (LEO) region. The training data is generated using the numerical Test Particle Monte Carlo (TPMC) method. TPMC is simulated with Cercignani–Lampis–Lord (CLL) gas-surface interaction (GSI) model. Mehta et al. [1] use a Gaussian process regression (GPR) model to predict satellite drag coefficient, but the authors did not estimate the predictive uncertainty. The first part of this research extends the work by Mehta et al. [1] by fitting a GPR model to the training data and performing predictive uncertainty estimation. The results of the Gaussian fit are then compared against a deep neural network (DNN) model aided by the Monte Carlo dropout approach. To the best of our knowledge, this is the first study to use the aforementioned stochastic deep learning algorithm to perform predictive uncertainty estimation of the estimated satellite drag coefficient. Apart from the accuracy of the models, we also undertake the task of calibrating the models. Simulations are carried out for a spherical satellite followed by the Champ satellite. Finally, quantification of the effect of drag coefficient uncertainty on orbit prediction is carried out for different solar activity and geomagnetic activity levels.

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AAS 21-575

ADVANCE THERMOSPHERIC DENSITY PREDICTIONS THROUGH FORECASTING GEOMAGNETIC AND SOLAR INDICES BASED ON GAUSSIAN PROCESSES

Yiran Wang,[*] Hao Peng,[†] Xiaoli Bai,[‡] Jason T. L Wang,[§] Haimin Wang[**]

For satellites at low altitudes, atmospheric drag is the dominant perturbation force, and neutral mass density is presently the predominantly uncertain term. The assumed parametric formulas could limit the current empirical models. This paper proposes a Gaussian Processes (GPs) based, data-driven density prediction framework that integrates information from empirical models, environment information, and satellite measurement data. This framework is an advancement over our previous work which has demonstrated that the proposed method achieves better accuracy than the empirical models, can be used for forecasting, and furthermore, provides quality uncertainty estimations. This new paper overcomes one of the previous limitations through including geomagnetic index forecasting. First, assuming the true geomagnetic index are available, we show the effectiveness to having this information from two aspects: 1) statistical prediction performance; 2) the importance of the input variables from the GPs framework. Next, we show how having degraded forecasting Dst values will affect the density prediction.

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AAS 21-638

A GLOBALLY AVERAGED THERMOSPHERIC DENSITY DATA SET DERIVED FROM TWO-LINE ORBITAL ELEMENT SETS AND SPECIAL PERTURBATIONS STATE VECTORS

J. T. Emmert,[*] M. S. Dhadly,[†] and A. M. Segerman[‡]

We describe a long-term data set of global average thermospheric mass density derived from orbit data on ~7700 objects in low Earth orbit, via the effect of atmospheric drag. The data cover the years 1967–2019 and altitudes 250–575 km, and the temporal resolution is 3–4 days for most years. The data set is an extension and revision of a previous version. The most important change is the use of more precise orbit data: special perturbation state vectors are now used starting in 2001, instead of mean Keplerian orbital elements. The data are suitable for climatological studies of thermospheric variations and trends, and for space weather studies on time scales longer than 3 days.

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AAS 21-646

SIX DEGREE-OF-FREEDOM TERMINAL REENTRY ANALYSIS USING VARIOUS SATELLITE BUS CONFIGURATIONS[*]

Jinhee F. Byun,[†] Robert A. Bettinger,[‡] and Jacob C. Olsen[†]

A six degree-of-freedom (6DOF) analysis of various conventional satellite bus configurations during atmospheric reentry is presented. Accounting for demisability is an integral step of designing and manufacturing satellites. With disposable equipment on board, the emphasis on structural strength and robust thermal protection system (TPS) pales for a conventional satellite in comparison to reentry capsules, which are specifically designed to withstand the intense aerothermodynamic effects experienced during reentry. However, if the satellite contains sensitive or critical assets on board, it may be essential to ascertain and quantify these environmental effects in order to ensure its survivability. This research examines the terminal reentry characteristics of common satellite bus geometry and solar panel array, including aerodynamic and thermal loading, and the deceleration experienced by the satellite body.

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[*] The views expressed are those of the authors and do not reflect the official guidance or position of the United States Government, the Department of Defense or of the United States Air Force.

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AAS 21-689

ATTITUDE CONTROL OF A MORPHABLE ENTRY SYSTEM FOR SMALL SATELLITE AEROCAPTURE AT MARS

Jannuel V. Cabrera* **and David A. Spencer†**

Aerocapture is an aeroassist maneuver that can enable small satellites to perform orbit insertion at interplanetary destinations. A semi-rigid deployable aeroshell concept called the morphable entry system is introduced for small satellite aerocapture at Mars. The morphable entry system is envisioned to employ shape-morphing for trajectory control during atmospheric flight. To assess the feasibility of this approach, this paper develops an angle of attack controller to manage the in-plane motion of the vehicle during aerocapture. The controller is integrated into an existing aerocapture guidance architecture to simulate aerocapture at Mars. The results indicate that the morphable entry system can successfully follow a desired angle of attack profile using shape-morphing. These results suggest that shape-morphing for aerocapture trajectory control at Mars is feasible with the morphable entry system.

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THREE-DIMENSIONAL ATMOSPHERIC DESCENT AND LANDING VIA MULTIPLE-SLIDING-SURFACE GUIDANCE*

Edoardo M. Leonardi,† Alessandro Vitiello,‡ and Mauro Pontani§

A multiple-sliding-surface technique is proposed as a real time guidance approach, for the purpose of driving an unpowered lifting vehicle along its descent path. Successful touchdown corresponds to reaching a specified landing site, with limited vertical velocity and prescribed heading angle, aligned with the runway. The time derivatives of the lift coefficient and bank angle are used as the control inputs. These two variables are constrained to suitable intervals for practical feasibility, so that only realistic trajectories can be generated by the guidance algorithm. Moreover, a new approach is proposed that allows selecting the convergence rate toward the sliding surfaces, based on adaptive coefficients. This study also addresses the heuristic optimization of the guidance gains, in a way that guarantees safe landing conditions with nearly-horizontal attitude and limited values of the angle of attack. Accuracy of the guidance technique at hand is proven numerically by means of a Monte Carlo campaign, in the presence of stochastic wind and large dispersions on the initial conditions.

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AAS 21-774

SCALING ATMOSPHERIC DENSITY COVARIANCE INFORMATION TO ESTIMATE ATMOSPHERIC DENSITY ACCURACY FOR SATELLITES WITH PRECISION ORBIT DATA AND WITHOUT AN ACCELEROMETER

Craig A. McLaughlin*

Precision orbit ephemerides (POE) have been used as measurements to estimate atmospheric density along the orbits of CHAMP and GRACE as part of an orbit estimation process. These estimated densities were then compared to accelerometer-derived densities to estimate the accuracy of POE-derived densities. POE-derived densities can also be found from satellites with POE data without accelerometers, but the accuracy must be estimated with a different technique. The RMS difference between POE and accelerometer-derived densities are compared to the density covariance information for CHAMP and GRACE. The CHAMP density covariance is then scaled to RMS level to estimate density accuracy for ANDE-2.

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AAS 21-782

NEURAL NETWORK BASED ESTIMATION OF ATMOSPHERIC DENSITY DURING AEROBRAKING

Amrutha Dasyam,[*] Pardhasai Chadalavada,[†] Charles A. Fry,[‡] Atri Dutta,[§] and Craig McLaughlin[**]

In this paper, we consider the aerobraking maneuver in which a spacecraft makes multiple passages through a planet's atmosphere to decelerate to a low-altitude orbit. Mission design for the aerobraking maneuver relies on the precise knowledge of the atmospheric density that is affected by a number of local factors. In this paper, we propose a neural network based methodology that utilizes knowledge about an atmospheric passage to compute the expected atmospheric density during the next atmospheric passage. We outline the performance of the neural network through numerical simulations by using Mars Global Reference Atmospheric Model as the true model of atmospheric density.

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DEBRIS AND SPACE ENVIRONMENT

Session Chairs:

Session 27: Davide Amato, Imperial College London

AAS 21-525

ARTIFICIAL DEBRIS PROPAGATION IN CISLUNAR PERIODIC ORBITS

Adam P. Wilmer,* Nathan R. Boone,† and Robert A. Bettinger‡

With the prospect of space travel becoming more frequent in the near future due to ongoing Artemis missions, it is critical to find methods which reduce waste, increase effectiveness, and provide a safe means for mission readiness. In particular, cislunar periodic orbits may provide a reliable astrodynamical architecture of supporting missions such as re-supply, personnel transport, space-based infrastructure development, and space traffic management within the Earth-Moon system. This research seeks to analyze the effects of a catastrophic spacecraft mishap in various cislunar periodic orbit in terms of risks to another notional spacecraft in the same periodic orbit as well as the risks to other regions of cislunar space. Specifically, eight mishap event scenarios are simulated on each of the five cislunar periodic orbits analyzed. Catastrophic explosion aftermath trajectories are analyzed at specified initial breakup locations on each periodic orbit to fully realize the repercussions of such a scenario. It was determined that each case study threatens unique regions of cislunar space; however, the overall risk to spacecraft is very low in each case. Overall, research into periodic orbit debris propagation enhances operational planning for future Earth-Moon space traffic management and develops an understanding of the debris-related consequences of spacecraft mishaps along cislunar periodic orbits.

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AAS 21-548

DEBRIS ATTITUDE EFFECTS ON ELECTROSTATIC TRACTOR RELATIVE MOTION CONTROL PERFORMANCE

Julian Hammerl* and Hanspeter Schaub†

The Electrostatic Tractor (ET) concept utilizes attractive Coulomb forces to relocate retired satellites from Geostationary Earth Orbit (GEO) to a graveyard orbit several hundred kilometers above GEO without any physical contact. Prior research investigated the charged relative motion control performance of the ET for two spherical spacecraft, and how electric potential uncertainty affects the control stability. This work utilizes the Multi-Sphere Method (MSM) to consider general three-dimensional spacecraft shapes, and investigates how the attitude of the debris and electric potential uncertainty affect the control effort and reorbit time. The results show that the reorbit time is minimized if protruding structures of the debris, such as solar panels, are directed toward the servicing satellite. The control effort, on the other hand, is only marginally affected by the debris attitude. Electrostatic torques generally cause the debris to tumble, and Monte Carlo simulations show that the rotation of the debris averages out the effects of debris attitude on control effort and reorbit time. However, the sensitivity of the controller to electric potential estimation errors is not entirely eliminated by a tumbling debris.

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COUPLED STATE PREDICTIONS WITH MULTIRATE RUNGE KUTTA INTEGRATION

Katharine E. Fisher* and Brandon A. Jones†

We propose a multirate numerical integrator to predict the dynamics of high area-to-mass ratio (HAMR) objects in Earth orbit. These objects have highly coupled orbit and attitude dynamics which are sensitive to solar radiation pressure (SRP). State of the art numerical methods generally use small time steps to accurately capture attitude dynamics. Multirate methods allow for coupled propagation that uses small steps for attitude dynamics and larger steps for orbital dynamics. Thus, these methods could result in an improvement in computational speed without sacrificing accuracy. These simulations could be used to prevent collisions of fast moving debris with spacecraft as well as for debris cleanup efforts. In this work, we review the equations of motion which govern HAMR objects in space as well as the mathematical formulation of an additive multirate Runge Kutta integrator. We present results from numerical case studies which compare the speed and accuracy of the multirate method to an embedded Runge Kutta 8(7) integrator. The multirate method is able to achieve computational speed ups compared to the baseline method and accurately propagates the translation state of HAMR debris. A greater level of error accrues in the attitude state propagation, and future work should seek to understand and control this error.

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COVERAGE CALCULATION AND ANALYSIS OF CONSTELLATIONS FOR SPACE-BASED OBSERVATION

Yangyuxi Sun,* Changxuan Wen,† and Dong Qiao‡

Space-based observation constellations, as a complement to traditional ground-based observation systems, have advantages in flexibility and observing performance, especially for very small space objects. Coverage calculation is essential for the constellation design. In this study, a rapid spatial coverage calculation method, for constellation with dual-altitude band and space-background observing constraints, is proposed. Firstly, the target region is discretized into the equal ring elements in the inertial spherical coordinate system. Meanwhile, its centerline is used as the coverage determination of this discrete element. Then, the coverage azimuth angle interval of the satellite for the determination circle is derived from the geometric relationship between sensor and target region. Finally, the multi-fold coverage of the constellation is calculated by superimposing the coverage of multiple satellites in the azimuthal dimension. Numerical examples demonstrate extensive constellation coverage calculations and constellation selection based on a combination of minimum cost and optimal performance.

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AAS 21-712

MODELLING THE WHOLE SPACE DEBRIS ENVIRONMENT THROUGH A SPATIAL DENSITY APPROACH

Cristina Duran,* Lorenzo Giudici,† and Camilla Colombo‡

This paper proposes a continuum density approach for analyzing the impact of a fragmentation event into the global debris environment. The debris population in LEO is represented through its spatial density, defined as a function depending only on the radial distance from the Earth. The time evolution of the density function is modelled through the continuity equation, considering the atmospheric drag effect. At a certain instant, a fragmentation cloud is generated. After the band formation, its contribution is added to the background population, analyzing the evolution of the total spatial density function. Finally, a novel formulation is introduced to also take into account the effect of the secondary phenomena derived from a collision or explosion in space. In particular, a chain of concatenated collisions, triggered by a single original fragmentation event, is considered, as well as its feedback effect on the overall debris population. Results are presented for three different scenarios to illustrate the long-term repercussions of fragmentation events.

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ROBOTICS, AUTONOMY, AND ARTIFICIAL INTELLIGENCE

Session Chairs:

Session 28: Anirudh Chhabra, University of Cincinnati

AAS 21-540

SPACECRAFT RENDEZVOUS, DOCKING, AND POST-DOCKING MANEUVERS UNDER LARGE UNCERTAINTIES VIA SWARM OPTIMIZED SIMPLE ADAPTIVE CONTROL

Andriy Predmyrskyy[*] and Steve Ulrich[†]

Improvements in simple adaptive control design are applied to a simulated active debris deorbit mission with thruster saturation and a target of unknown mass properties. The same controller is used across rendezvous, docking, and post-docking control of the target. Large uncertainty in dynamics of the rigidly docked system are managed and compensated by the adaptive controller. Cross-coupling present between the position and orientation response are automatically compensated by the adaptive controller. Swarm optimization techniques are used to simplify controller design, and nonlinearity in the rendezvous dynamics are compensated using a path planning optimization. Adaptive control is able to drastically diminish the effects of cross-coupling on the position and orientation response without a priori knowledge of the dynamics while improving command tracking.

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AAS 21-572

INTELLIGENT TASK PLANNING FOR AN AGILE OZONE OBSERVATION SATELLITE

Hao Peng[*] and Xiaoli Bai[†]

This paper presents a novel method to guide an agile Earth observation satellite for remote sensing, using measuring total column ozone (TCO) as the application. The resulting task planning is intelligent since it achieves the goal not only to find the extreme values but also to understand what happens across the whole studied area. We present a Bayesian Optimization based method to achieve the goal. In the nadir-pointing strategy, the satellite always points to and measure the nadir points. In the offset-pointing strategy, the satellite is guided by the BO-based tasking method to measure the location with either larger TCO values or higher model uncertainties. As demonstrated by the simulation results, the proposed tasking method can lead to both better prediction accuracy and precision of the TCO distribution. This reveals that the proposed BO-based strategy can enhance the efficiency and accuracy of the remote sensing satellite. A comparison with a deterministic offset-pointing method is also presented to demonstrate that the BO-based tasking method is indeed superior.

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AAS 21-589

A CONVOLUTIONAL NEURAL NETWORK APPROACH TO STAR SENSORS IMAGE PROCESSING ALGORITHMS

Marco Mastrofini,[*] Francesco Latorre,[†] Ivan Agostinelli,[‡] and Fabio Curti[§]

The present work will investigate an Artificial Intelligence (AI) approach in the framework of image segmentation and clustering algorithms for star sensors applications. It focuses on the architecture development and test of a Convolutional Neural Network (CNN) based algorithm and results comparison with the state of the art. The problem of image segmentation will be faced using the U-Net to detect the brightest objects in the sensor's Field Of View (FOV) for attitude determination purposes. The dataset creation for the network training, algorithm design process and definition of performance indices are provided together with comparison test results.

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AAS 21-639

AUTONOMOUS CROSS-CALIBRATION FOR IMAGING SATELLITES

Zvonimir Stojanovski* and Dmitry Savransky†

We present a fully autonomous image-based cross-calibration method for constellations of Earth-observing satellites. Here, each satellite extracts features from primary mission images and then transmits the features, along with its state estimate, to other satellites. Furthermore, each satellite uses comparisons of the image features, along with conventional state measurements, to estimate its position, attitude, and camera parameters via the unscented Kalman filter or the higher-order unscented estimator. We demonstrate the simulation framework for testing this method with an example featuring two imaging satellites. In the future, we will rigorously test the method's performance and refine the image-based measurement model.

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AAS 21-683

SPACECRAFT DYNAMICS MODEL LEARNING AND CONTROL WITH GAUSSIAN PROCESS REGRESSION

William Parker,* Keenan Albee,† and Richard Linares‡

Spacecraft motion under parametric unknowns arises in many on-orbit assembly, servicing, and assistance scenarios such as manipulation of an unknown grappled object. Traditionally, model-based control is effective in dealing with such unknowns, assuming a suitable parameter estimation method is available for a well-defined dynamics model. Even for more complex spacecraft, detailed analysis is often performed prior to launch to provide a suitable dynamics model for flight operations. Recently, however, interest in satellite servicing, on-orbit assembly, and debris removal has introduced new problems for controlling spacecraft whose dynamics might not be easily described by parametric unknowns, or whose models might differ significantly from a simpler assumed model. It is highly desirable to learn and adapt to arbitrary system model changes for cases where traditional parametric estimation is insufficient. Utilizing advances in applying stochastic process regression to dynamics learning problems, the authors propose a new approach for learning unknown "hard-to-model" spacecraft dynamics in a non-parametric way using Gaussian process regression techniques. This approach allows unmodeled dynamics to be learned onboard a spacecraft (and in real-time) with, for example, an uncertain or time-varying mass distribution, geometry, or control authority. This approach is also demonstrated as a useful tool for fault detection, identification, and recovery (FDIR), to help identify and adapt to issues like actuator degradation or failure during a spacecraft's operating lifetime. The approach is discussed in relation to traditional parameter estimation methods, and demonstrated for a case study of the rigid and flexible satellite grappling dynamics.

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MISSION DESIGN AND TRAJECTORY OPTIMIZATION

Session Chairs:

Session 29: Ossama Abdelkhalik, Iowa State University

The following paper listed in the conference program was not presented:

AAS 21-633

AAS 21-547

ECLIPSE-CONSCIOUS TRANSFERS TO LUNAR GATEWAY USING EPHEMERIS-DRIVEN TERMINAL COAST ARCS

Sandeep K. Singh,[*] Brian D. Anderson,[†] Ehsan Taheri[‡] and John L. Junkins[§]

A novel indirect-based trajectory optimization framework is proposed that leverages ephemeris-driven, “invariant manifold analogues” as long-duration asymptotic terminal coast arcs while incorporating eclipses and perturbations during the optimization process in an ephemeris model; a feature lacking in state of the art softwares like MYSTIC and Copernicus. The end-to-end trajectories are generated by patching Earth-escape spirals to a judiciously chosen set of states on pre-computed manifolds. The results elucidate the efficacy of the proposed trajectory optimization framework using advanced indirect methods and by leveraging a Composite Smooth Control (CSC) construct. Multiple representative cargo re-supply trajectories are generated for the Lunar Orbital Platform-Gateway (LOP-G). The results quantify accurate ΔV costs required for achieving efficient eclipse-conscious transfers for several launch opportunities in 2025 and are anticipated to be used for analogous uncrewed lunar missions.

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AAS 21-568

REINFORCEMENT LEARNING FOR RECONFIGURATION MANEUVER DESIGN IN MULTI-BODY SYSTEMS

Natasha Bosanac,[*] Stefano Bonasera,[†] Christopher J. Sullivan,[†] Jay McMahon,[‡] and Nisar Ahmed[§]

Reinforcement learning is used to design reconfiguration maneuvers for a spacecraft to adjust its position relative to another spacecraft located along an L_2 halo orbit in the Sun-Earth circular restricted three-body problem. This specific scenario is modeled after a starshade reconfiguring to block starlight while a space telescope observes exoplanets. First, reconfiguration maneuver design is translated into a reinforcement learning problem. Then, Proximal Policy Optimization is used to train a policy that generates sequences of impulsive reconfiguration maneuvers. The trained policy is examined and used to produce reconfiguration maneuver sequences that successfully achieve the reconfiguration goals with low maneuver magnitudes.

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THREE-TARGET GROUND-TRACK ADJUSTMENT WITH A SINGLE COPLANAR IMPULSE

Xin Lin,* Gang Zhang,† and Haiyang Zhang‡

The ground-track adjustment problem for overflying three ground targets with a single coplanar impulse is studied by considering the J_2 perturbation. The original multi-dimensional problem is transformed into solving the roots of a one-dimensional function only of maneuver position, which can be solved by numerical iterative algorithms, e.g., the piecewise golden section search and the secant method. In addition, the short-period term of semimajor axis is considered and it is proven to effectively reduce the overflight error. Numerical examples are provided to verify the effectiveness of the proposed method for solving the ground track adjustment problem for three ground targets.

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AAS 21-605

NEW TOOLS FOR TOUR DESIGN: SWISS CHEESE PLOT, INVARIANT FUNNEL, AND RESONANT ENCOUNTER MAP

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

We define a new set of tools for tour design introduced in previous work: the "Swiss Cheese Plot," "Invariant Funnel," and "Resonant Encounter Map." These tools promise to be useful in designing, analyzing, and navigating low-energy trajectories through multi-body systems. We review and clarify methods for generating the swiss cheese plot and invariant funnels in the Circular Restricted Three-Body Problem. We introduce the resonant encounter map as a graphical representation of the three-body design space, similar to the pork-chop plot for the two-body problem. We also discuss some interesting characteristics of the resonant encounter map and its connection to the invariant manifolds of periodic libration orbits.

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AAS 21-653

MULTI-OBJECTIVE HIDDEN GENES OPTIMIZATION OF SPACE TRAJECTORIES

Ahmed Ellithy,[*] Ossama Abdelkhalik,[†] and Jacob Englander[‡]

Optimizing a trajectory with only one objective may restrict mission designers since sometimes multiple objectives are of interest. This study deals with multi-objective optimization of impulsive trajectories where the objectives are the total fuel consumption and the total time of flight. The number of flybys, flyby sequence, locations and values of the deep space maneuvers are unknown variables. This renders the problem a variable-size design space optimization problem. This multi-objective hidden genes genetic algorithm (MOHGGA) is tested on benchmark problems, and the results are presented in this paper.

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ATTITUDE AND GUIDANCE, NAVIGATION, AND CONTROL

Session Chair:

Session 30: Marcus Holzinger, University of Colorado Boulder

EQUIVALENCE OF LINEARIZED APPROXIMATIONS FOR OVERPARAMETERIZED REPRESENTATIONS OF DYNAMIC SYSTEMS

Andrew J. Sinclair* and Eric A. Butcher†

Many developments in astrodynamics have focused on alternative coordinate systems for the description of spacecraft translational and rotational motion, generally resulting in nonlinear dynamic systems. Related to this, recent work has demonstrated the equivalence between linearized approximations of minimal coordinate systems. However, the description of rotational kinematics often utilizes over-parameterized representations. Therefore, this paper demonstrates the equivalence between linearized approximations for overparameterized representations of dynamic systems.

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AAS 21-652

ASTROBATICS SESSION 1: SELF-TOSS MANEUVERS WITH ASTROBEE ONBOARD THE INTERNATIONAL SPACE STATION

Stephen Kwok-Choon,[*] Jennifer Hudson,[†] Daniel Watanabe,[‡] James Summerlin,[‡] Ian Hardy,[‡] and Marcello Romano[§]

The first of five Astrobatics experimental sessions was performed on-board the International Space Station with the free-flyer vehicle Astrobee and consisted of eight self-toss maneuvers with eighteen different runs. Astrobatics aims to explore self-toss maneuvers of Astrobee using its robotic arm as a method of locomotion for orbital robotic activities by a spacecraft-manipulator system. The Astrobee three degree-of-freedom robotic arm is composed of a two-revolute-joint, two-link system, attached to a three-finger gripper. This paper aims to describe the experiment session, observations, limitations, and an in-depth discussion of two self-toss maneuvers, with an outline for the future Astrobatics sessions.

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AAS 21-680

INCORPORATING DELAYED STAR TRACKER MEASUREMENTS IN ATTITUDE FILTER

Ozgur Kahraman[*] and Halil Ersin Soken[†]

Star trackers (STRs) are widely used for fine attitude estimation. Due to the processing time for tasks such as star identification, tracking and attitude solution, a STR can provide the attitude quaternion measurements with a time-delay, which may be as high as few 100 milliseconds. There are different methods available for incorporating such delayed measurements in the attitude filter, such as the most straightforward method of propagating the measurements to the actual filter time. This study evaluates different methods to incorporate delayed STR measurements in the attitude filter, which is structured as a Multiplicative Extended Kalman Filter (MEKF). Methods are compared in terms of accuracy, computational load and their impact on the filter's optimality. They are both evaluated using the simulated data for an Earth observation spacecraft in Sun-synchronous orbit and the logged real STR data for a similar spacecraft.

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AAS 21-692

INVARIANT EXTENDED KALMAN FILTER FOR FULL–STATE SPACECRAFT NAVIGATION

Daniel Newberry* and Henry Pernicka†

Two invariant filters are developed that provide full–state estimation of spacecraft motion modeled by the circular restricted three–body problem (CR3BP). These filters, the left–invariant extended Kalman filter (LIEKF) and the right–invariant extended Kalman filter (RIEKF), are based on two different but equivalent representations of the same system. These invariant filters leverage the Lie group structure that is the true representation of the spacecraft state space instead of assuming a vector space structure. This acknowledgement allows for a preservation of the structure of the state space in the update. As a comparison, a multiplicative extended Kalman filter (MEKF) is developed for the same system as a baseline for performance assessment. Through a Monte Carlo simulation with 400 independent trials, the invariant filters achieved significant increases in the confidence interval in the attitude and attitude rate estimation errors while having comparable performance in the position and velocity estimation errors. While the right–invariant filter performed worse for the position and velocity states, other systems or additions of structured perturbations may result in better relative performance.

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AAS 21-699

ANGULAR VELOCITY ESTIMATION USING RATE-INTEGRATING GYRO MEASUREMENTS

S. P. Arjun Ram,[*] Maruthi R. Akella,[†] and Renato Zanetti[‡]

Rate Integrating Gyroscopes (RIGs) measure integrated angular rates or angular displacement, requiring an observer to provide full state feedback to the attitude controller. The problem of estimating the angular velocity of a rotating rigid body with known inertia and torque, using measurements from a rate integrating gyro is considered. A nonlinear observer is designed that uses only continuous-time RIG measurements and provides estimates of the angular velocity. Moreover, the observer is shown to be robust to bounded inaccuracies in the knowledge of inertia and external torque acting upon the system while the state estimation error converges exponentially to zero when the model is perfect. The observer is tested in simulation to demonstrate its effectiveness.

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AAS 21-748

EXTENSION OF UDWADIA-KALABA CONSTRAINED MOTION ANALYSIS TO INEQUALITY CONSTRAINTS WITH APPLICATIONS TO TRAJECTORY MAINTENANCE

Brennan S. McCann*[*] and Morad Nazari[†]

Udwadia and Kalaba developed a formalism for constrained motion analysis of a system of particles subject to equality constraints. Presented here is a generalization of Udwadia-Kalaba (U-K) formalism to address inequality constraints. Two methodologies are introduced for this purpose. In the first technique, slack variables are used to convert the inequality constraints to equality constraints so that they can be formulated in the U-K framework. In the second technique, a family of the Gaussian distribution function is used to avoid singularities and impulsive control inputs. These techniques enable one to address the inequality constraints without a need to compute Lagrange multipliers. The proposed methodologies are applied to the problem of spacecraft trajectory maintenance in lunar orbit under the influence of an unmodeled, non-uniform gravity model, where the spacecraft is constrained to remain within a certain radius of a reference trajectory.

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AAS 21-752

FLASH LIDAR AIDED-INERTIAL NAVIGATION ON SURFACES OF SMALL SOLAR SYSTEM BODIES USING ERROR STATE KALMAN FILTERING

B. Liu,[*] V. Sazdovski,[†] V. Chernykh,[‡] and K. Janschek[§]

We propose a novel navigation solution for low-height, hovering and moving spacecraft for advanced surface mobility for exploration operations on surfaces of small solar system bodies. We formulate the solution as aided inertial navigation. No a priori knowledge of the ground surface is assumed. Full scan-matching between two consecutive point clouds from a Flash LIDAR is used to calculate optimal relative rigid transformation (translation and rotation) and provide the observations to an error state Kalman filter. A novel observation model is formulated around this point cloud registration scheme. Errors in the position and attitude once estimated in the error state Kalman filter are sent to an independent inertial navigation system for correction. The results presented in a specialized high fidelity simulated environment show the viability of this novel navigation solution.

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AAS 21-753

REFERENCE TRAJECTORIES FOR ARBITRARY TRACK-TO-TRACK ATTITUDE MANEUVERS

Andrew J. Miller[*] and Maruthi R. Akella[†]

We propose a closed-form attitude reference trajectory for track-to-track maneuvers. The trajectory is patched through three separately designed phases: a de-spin phase, a rest-to-rest phase, and a spin-up phase. During each phase, a simple recursion is introduced to satisfy torque saturation specifications. While each phase is computed in a smoothed time-optimal sense, the time of flight for the resulting full trajectory is sub-optimal. In return, this performance trade-off offers algorithmic simplicity, lightweight computations, and guarantees that the attitude reference trajectory can be determined for arbitrary boundary conditions, making it well suited for real-time implementations. Numerical simulation of a track-to-track maneuver is presented to showcase the various features of the proposed algorithm.

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