2024 AAS/AIAA Astrodynamics Specialist Conference, Broomfield, Colorado, August 11-15, 2024

American Astronautical Society

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Conference Information

General Information

The 2024 AAS/AIAA Astrodynamics Specialist Conference, hosted by the American Astronautical Society (AAS) and co-hosted by the American Institute of Aeronautics and Astronautics (AIAA) will be held August 11-15, Broomfield, Colorado. The conference is co-sponsored by Advanced Space and organized by the AAS Space Flight Mechanics Committee and the AIAA Astrodynamics Technical Committee.

Registration

Registration can be accessed at
https://www.xcdsystem.com/aas/attendee/index.cfm?ID=68BHEdL

Registration Type	Early (On or before Jul 10, 2024 ET)	Regular (Jul 11 - Aug 10, 2024 ET, inclusive)	Walkups (On or after Aug 11, 2024 ET)
Full Registration - Current Member (AAS or AIAA)	$765	$835	$935
Full Registration - Non-member, includes one-year AAS membership	$865	$935	$1,035
Student Registration - Current Member (AAS or AIAA)	$450	$520	$620
Student Registration - Non-member, includes one-year AAS membership	$495	$565	$665
Retiree Registration - Current Member (AAS or AIAA)	$450	$520	$620
Retiree Registration - Non-member, includes one-year AAS membership	$500	$570	$670

The online registration system is programmed to accept Visa, Mastercard, Discover and American Express credit cards.

NOTE: Registration fees are calculated at the time of payment. Beginning the registration process without completing payment may result in a higher fee being charged as applicable based upon the early/late/on-site fee schedule set by the General Chairs.

Conference Proceedings

We are delighted to continue utilizing Springer Nature as our publisher for conference proceedings.

NOTE: One electronic proceedings for download is included with every Full Registration.

If you did not register with a Full Registration OR wish to purchase additional proceedings for download, you can do so during the online registration process.

Sponsors

Advanced Space (https://advancedspace.com/) exists to enable the sustainable exploration, development, and settlement of space through software and services that leverage unique subject matter expertise to improve the fundamentals of spaceflight. The company is actively supporting mission and cutting-edge capabilities spanning commercial, civil, international and national security customers. Through its Mission Enabling Services, Advanced Space provides mission and flight optimization, mission design, and mission systems engineering. With its Technology Solutions Advanced Space provides its customers with trusted AI/ML/autonomy expertise, flight-demonstrated applications, and analysis at scale. Advanced Space offers Mission Solutions with unique rapid turn-key missions, data and capabilities purchases as well as demonstrated cislunar and Martian success. Advanced Space is the owner and operator of CAPSTONE™ for NASA and Prime contractor for Oracle for AFRL. Trusted to take on the challenge, the team at Advanced Space is Delivering Innovation to Orbit™ to the Moon, Mars, and beyond.

Conference Location

General Inquiries
https://www.omnihotels.com/hotels/denver-interlocken
Omni Interlocken Resort
500 Interlocken Boulevard
Broomfield, Colorado, 80021, USA
Phone:+1 303-438-6600
Toll-free:+1 800-THE-OMNI

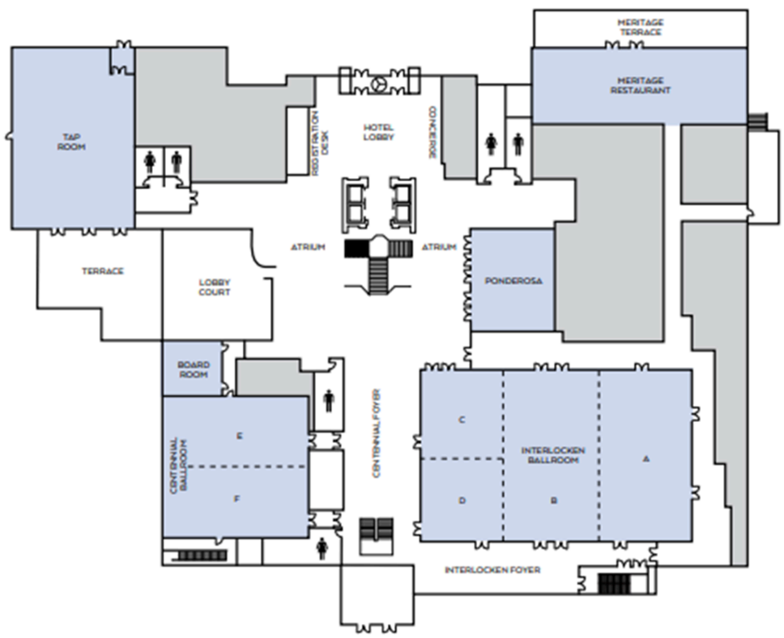
Conference Reservations
To book hotel room at the conference rate please use the following link:
https://bookings.omnihotels.com/event/denver-interlocken/aas-astrodynamics-specialists-conference-08102024
Online reservation link for AAS 2024

Additional Information
The nightly rooms rates are $176 per night:

- Rates will be at the prevailing government per diem at the time of the conference
- Deluxe WiFi - please access with password **aas2024** in the conference area
- 2 Bottles of Water Per Stay
- Local Calls
- Complimentary use of golf driving range and practice facilities, including rental clubs if needed
- Access to Resort facilities including Outdoor Heated pool, Hot tub, fire pits, and fitness center
- Complimentary Parking

Map of Conference Area in Omni Hotel

LOBBY LEVEL



GARDEN LEVEL

Things to do

Courtesy of the Omni Interlocken Hotel Concierge, see the link below for Concierge Picks Area Attractions and Shopping!

Fun Things to Do!

https://www.omnihotels.com/hotels/denver-interlocken/property-details/gallery

Schedule of Events

Room locations subject to change; please refer to on-line program for latest updates.

Start	End	Event	Room
Sunday, 8/11/2024			
6:00 PM	6:00 PM	Registration	Atrium
6:00 PM	9:00 PM	Reception	Pavilion/Lawn
Monday, 8/12/2024			
7:30 AM	5:00 PM	Registration	Atrium
8:30 AM	10:00 AM	Cislunar Astrodynamics I	Pinon
8:30 AM	10:00 AM	Space Domain Awareness (SDA) and Space Surveillance I	Pine
8:30 AM	10:00 AM	Spacecraft Guidance, Navigation and Control (GNC) I	Centennial E
8:30 AM	10:00 AM	Trajectory, Mission, and Maneuver Design/Optimization I	Centennial F
10:30 AM	12:30 PM	Trajectory, Mission, and Maneuver Design/Optimization II	Centennial F
10:30 AM	12:30 PM	Cislunar Astrodynamics II	Pinon
10:30 AM	12:30 PM	Spacecraft Guidance, Navigation, and Control (GNC) II	Centennial E
10:30 AM	12:30 PM	SPECIAL SESSION: Astrobotic Peregrine	Pine
12:30 PM	2:00 PM	AAS/AIAA Joint Committee Meeting	Meritage
2:00 PM	3:15 PM	Attitude Dynamics, Determination, and Control I	Centennial E

2:00 PM	3:15 PM	Orbital Debris and Space Environment I	Pine
2:00 PM	3:15 PM	Trajectory, Mission, and Maneuver Design/Optimization III	Centennial F
3:45 PM	5:00 PM	Attitude Dynamics, Determination and Control II	Centennial E
3:45 PM	5:00 PM	Earth Orbital and Planetary Mission Studies	Pine
3:45 PM	5:00 PM	Orbit Determination and Estimation II	Centennial F
5:00 PM	6:00 PM	Reception Cocktail	Centennial Foyer
6:00 PM	7:00 PM	AAS Awards and Brouwer Lecture	Centennial Ballroom
Tuesday, 8/13/2024			
7:30 AM	5:00 PM	Registration	Atrium
8:30 AM	10:00 AM	Atmospheric Re-entry Guidance and Control	Pine
8:30 AM	10:00 AM	Cislunar Astrodynamics III	Pinon
8:30 AM	10:00 AM	Dynamical Systems Theory Applied to Spaceflight Problems I	Centennial E
8:30 AM	10:00 AM	Space Domain Awareness (SDA) and Space Surveillance II	Centennial F
10:30 AM	12:30 PM	Cislunar Astrodynamics IV	Pinon
10:30 AM	12:30 PM	Orbit Determination and Estimation III	Pine
10:30 AM	12:30 PM	Spacecraft Guidance, Navigation and Control (GNC) III	Centennial E
10:30 AM	12:30 PM	Trajectory, Mission, and Maneuver Design/Optimization V	Centennial F
2:00 PM	3:15 PM	Asteroid and Interplanetary Mission Design I	Pinon

2:00 PM	3:15 PM	Dynamical Systems Theory Applied to Spaceflight Problems II	Centennial E
2:00 PM	3:15 PM	Orbit Determination and Estimation IV	Pine
2:00 PM	3:15 PM	Trajectory, Mission, and Maneuver Design/Optimization VI	Centennial F
3:45 PM	5:00 PM	Dynamical Systems Theory Applied to Spaceflight Problems III	Centennial E
3:45 PM	5:00 PM	Orbit Determination and Estimation V	Pine
3:45 PM	5:00 PM	Rendezvous, Relative Motion, and Proximity Operations I	Pinon
3:45 PM	5:00 PM	Trajectory, Mission, Maneuver and Design/Optimization VII	Centennial F
6:00 PM	9:00 PM	Dinner and Entertainment	Pavilion/Lawn
Wednesday, 8/14/2024			
7:30 AM	5:00 PM	Registration	Atrium
8:30 AM	10:00 AM	Cislunar Astrodynamics V	Pinon
8:30 AM	10:00 AM	Dynamical Systems Theory Applied to Spaceflight Problems IV	Centennial E
8:30 AM	10:00 AM	Satellite Constellations and Formations	Centennial F
10:30 AM	12:30 PM	Cislunar Astrodynamics VI	Pinon
10:30 AM	12:30 PM	Trajectory, Mission, and Maneuver Design/Optimization VIII	Centennial F
10:30 AM	12:30 PM	Space Situational Awareness, Conjunction Analysis, and Collision Avoidance I	Pine
10:30 AM	12:30 PM	Spacecraft Guidance, Navigation and Control (GNC) IV	Centennial E

2:00 PM	3:15 PM	Orbital Dynamics, Perturbations, and Stability I	Centennial E
2:00 PM	3:15 PM	Rendezvous, Relative Motion, and Proximity Operations II	Pinon
2:00 PM	3:15 PM	Trajectory, Mission, and Maneuver Design/Optimization IX	Centennial F
2:00 PM	3:15 PM	Asteroid and Interplanetary Mission Design II	Pine
3:00 PM	4:00 PM	Journal of the Astronautical Sciences Editorial Board Meeting	Board Room
3:45 PM	5:00 PM	Machine Learning and Artificial Intelligence Applied to Spaceflight, Space Autonomy I	Centennial E
3:45 PM	5:00 PM	Rendezvous, Relative Motion, and Proximity Operations III	Pinon
3:45 PM	5:00 PM	Trajectory, Mission, and Maneuver Design/Optimization X	Centennial F
3:45 PM	5:00 PM	Asteroid and Interplanetary Mission Design III	Pine
5:00 PM	6:00 PM	Ice Cream Social Sponsored by Advanced Space	Centennial Foyer
6:00 PM	7:00 PM	OSIRIS-REx Navigation Special Session	Centennial Ballroom
7:00 PM	8:00 PM	Networking Event Sponsored by Advanced Space	TBD
Thursday, 8/15/2024			
7:30 AM	12:00 PM	Registration	Atrium
8:30 AM	10:00 AM	Asteroid and Interplanetary Mission Design IV	Centennial F

8:30 AM	10:00 AM	Machine Learning and Artificial Intelligence Applied to Spaceflight, Space Autonomy II	Centennial E
8:30 AM	10:00 AM	Orbital Dynamics, Perturbations, and Stability II	Pine
8:30 AM	10:00 AM	Rendezvous, Relative Motion, and Proximity Operations IV	Pinon
10:30 AM	12:30 PM	Machine Learning and Artificial Intelligence Applied to Spaceflight, Space Autonomy III	Centennial E
10:30 AM	12:30 PM	Orbital Debris and Space Environment II	Pinon
10:30 AM	12:30 PM	Orbital Dynamics, Perturbations, and Stability III	Pine
10:30 AM	12:30 PM	Space Situational Awareness, Conjunction Analysis, and Collision Avoidance II	Centennial F

Each session will have a break of 30 minutes in between. For the morning sessions (Monday to Thursday), the breaks are scheduled from 10:00 AM to 10:30 AM. For the afternoon sessions (Monday to Wednesday), the breaks are scheduled from 3:15 PM to 3:45 PM.

Special Event Information

On **Sunday, Aug 11**, there will be a welcome reception at the Omni Interlocken Resort's' Pavilion and (weather permitting) Lawn.

On **Monday, Aug 12**, we will have an awards reception and presentation. The reception will be 5-6 PM in the Centennial Foyer, and the awards presentation will begin at 6 PM in the Centennial ballroom. We will present the AAS "Emerging Astrodynamicist" award, AAS Fellows, John V. Breakwell Student Paper Awards, and Best Conference Paper Award. This will be followed by presentation of the Dirk Brouwer Award to Prof. Hanspeter Schaub, who will deliver the Dirk Brouwer Plenary Lecture.

On **Tuesday, Aug 13**, we will hold a dinner and social event in the Omni's Pavilion/Lawn. 6:00-9:00 PM There will be live country/bluegrass music from a local band and the opportunity to make your own AAS/AIAA coaster at a wood burning station. You may purchase additional tickets for each social event during the online registration process.

A special panel will be presented by the OSIRIS-REx astrodynamics team on **Wednesday, Aug 14** in the Centennial ballroom. Come learn first-hand from the astrodynamicists who designed and operated the 1st U.S. mission to collect a sample from the surface of the asteroid Bennu and returned the sample back to Earth! There will also be an **Ice-Cream Social** from 5-6pm and after the panel, a **Networking Event**- Sponsored by Advanced Space from **7-8 PM**

Tentative Agenda for Monday, Aug 12th, 2024:

5:00 - 5:55	**Reception Announcement/directions**
	Introductions from John Christian
6:00 - 7:30	**AAS Fellow Award**
	Presented by Jim Way
	JASS Outstanding Paper Award
	Presented by Prof. Maruthi Akella
	John V. Breakwell Student Paper Awards
	Presented by Prof. Natasha Bosanac
	AAS Emerging Astrodynamicist Award
	Presented by Prof. Dan Scheeres
	AAS Dirk Brouwer Award: Prof. Hanspeter Schaub
	Introduction from Renato Zanetti **Dirk Brower Plenary Lecture (45 + 10 min Q&A)**

Tentative Agenda for Tuesday, Aug 13th, 2024:

6:00 - 9:00	**Buffet Dinner and Entertainment**
	Introductions from John Christian
6:20 (approx)	**Dinner begins**

6:00 - 9:00	**Entertainment and Wood Burning Activity**
9:00 (approx)	**End of Dinner**

Tentative Agenda for Wednesday, Aug 14th, 2024:

5:00 - 6:00	**Ice Cream Social-Sponsored by Advanced Space**
	Centennial Foyer
6:00 - 7:00	**OSIRIS-REx Navigation Special Panel**
	Centennial Ballroom
7:00 - 8:00	**Networking Event- Sponsored by Advanced Space**
	Location TBA

Additional Technical Information

Author presentations (preferably in ppt or pdf format) will be submitted through a web-based system and are due by Wednesday July 27th, 2024, 23:59:59 Eastern Time. Each presentation is allocated a 15 minute time slot: approximately 12 minutes for the presentation itself and 3 minutes for questions and answers as well as a transition between speakers.

Presenters shall coordinate with their Session Chairs regarding the available computing equipment, software, and media requirements for the session. Microsoft PowerPoint and PDF are the most common formats and presentation slides must be uploaded by the specified deadline.

Authors are encouraged to be in their session room 15-30 minutes prior to the start of their sessions to confirm that their presentation appears correctly. No speakers' breakfast will be served. Authors should have submitted a brief (approximately 50 words or 3 sentences) speaker's bio with their abstract submission. Session chairs shall maintain the posted schedule to allow attendees the option of joining a parallel session.

"No-paper, no-podium" policy
Completed preprints shall be electronically uploaded to the submission site before the conference, limited to 20 pages in length, and conform to the AAS conference paper format.

Authors are reminded that the deadline to upload pre-prints to the https://www.xcdsystem.com/aas/ website is Saturday July 27th, 2024, 23:59:59 Eastern Time. A final paper upload will be due on or before September 6, 2024 23.59:59 Eastern Time including both pdf format and files in LaTeX or Word format.

If the completed manuscript is not submitted on time, it will not be presented at the conference. If there is no conference presentation by an author, the contributed manuscript shall be withdrawn.

Authors will be notified about the instructions to submit their paper for publication in the proceedings at a later time.

Each author also acknowledges that they are releasing technical information to the general public and that respective papers and presentations have been cleared for public release. If any author of a paper is a US person (citizen or permanent resident), they acknowledge that the release of these data and content of the paper and presentation conforms to ITAR and are not on the USML. The information contained in these documents is neither classified, SBU, FOUO, nor proprietary to any sponsoring organization.

Preprint manuscripts
Physical copies of preprinted manuscripts are no longer available or required for the Space Flight Mechanics Meetings or the Astrodynamics Specialist Conferences. Electronic preprints are available for download at least 72 hours before the conference at https://www.xcdsystem.com/aas/ for registrants who use the online registration system. Registrants without an internet-capable portable computer, or those desiring traditional paper copies should download and print preprint manuscripts before arriving at the conference.

Subsequent Journal Publication
Although the availability of proceedings enhances the longevity of your work and elevates the importance of your conference contribution, please note that conference proceedings are not considered an archival publication. Authors are encouraged to submit their manuscripts after the meeting to one of the relevant journals, such as:

Journal of the Astronautical Sciences
Editor-in-Chief: Dr. Maruthi Akella, The University of Texas at Austin
Manuscripts can be submitted via: https://www.editorialmanager.com/jass

Journal of Guidance, Control and Dynamics
Editor-in-Chief: Dr. Ping Lu, San Diego State University
Manuscripts can be submitted via: https://mc.manuscriptcentral.com/aiaa

Journal of Spacecraft and Rockets
Editor-in-Chief: Dr. Olivier de Weck, Massachusetts Institute of Technology
Manuscripts can be submitted via: https://mc.manuscriptcentral.com/aiaa

Committee meetings
Committee seating is limited to committee members and invited guests. Committee and subcommittee meetings will be held according to the schedule at the beginning of the program.

Conference Technical Presentation Schedule

Room locations subject to change; please refer to on-line program for latest updates.

Cislunar Astrodynamics I
Room: Pinon, Monday, August 12
8:30 AM - 10:00 AM
Session Chair(s): Dhruv Jain (Kayhan Space) and Brian McCarthy (a.i. solutions, Inc)

8:30 AM
AAS-104 : Propagation Best Practices for Cislunar Debris Mitigation and Disposal
Conor Benson (The Aerospace Corporation), Lucia Capdevila (The Aerospace Corporation), Joseph Gangestad (The Aerospace Corporation)

We present foundational best practices for accurate, long-term cislunar propagation on decade to century timescales. Many cislunar efforts including debris population modeling, collision avoidance, and post-mission disposal will require accurate, long-term cislunar trajectory propagation on these timescales. Traditional methods for short-term cislunar and long-term perturbed Keplerian propagation are inadequate for accurate, long-term cislunar propagation. We obtain best practices by exploring two parallel pathways: 1) numerical techniques that minimize error growth over successive lunar encounters, and 2) cislunar regions/trajectories that minimize “exposure” to lunar jerk and thereby minimize error growth.

8:45 AM
AAS-108 : Cislunar Uncertainty Growth with Applications to Conjunction Assessment
Carter Franz (The Aerospace Corporation), Travis Lechtenberg (The Aerospace Corporation), Eamonn Moyer (The Aerospace Corporation)

This work investigates and provides recommendations for uncertainty propagation for use in collision screening, develops insight into uncertainty growth in the cislunar regime, and informs operational practices and future SSA studies. Uncertainty in three-body orbits grows too large to be useful for collision screenings before it becomes meaningfully non-Gaussian, with this growth concentrated along the most stretching direction predicted by the Cauchy-Green tensor. Standard filter algorithms for geocentric collision screenings such as the extended and unscented Kalman filters can be readily applied to both lunar and cislunar orbits, with lunar orbits best represented with equinoctial orbital elements.

9:00 AM
AAS-175 : A Design Approach for Cislunar On-Orbit Servicing Networks
Cody Waldecker (Purdue University), Kathleen C. Howell (Purdue University)

Present work includes key considerations and strategies for designing networks of servicer/customer satellites in the Circular Restricted Three-Body Problem (CR3BP) and with validation in an Earth-Moon-Sun Ephemeris model. Poincaré maps are introduced for timing uninformed transfer design and, then, an auction algorithm is derived to overcome phasing challenges. Design techniques are demonstrated with a geometrically complex network of satellites located in halo orbits and bifurcating families, but the methods presented are agnostic to the underlying orbits and may be applied for ISAM or surveillance network design at any location in the cislunar region.

9:15 AM

AAS-117 : Novel Architecture for a Circular Polar Lunar Orbit Constellation

Amanda Marx (ispace Technologies U.S., Inc.), Fernando Gonzalez-Meruelo (ispace, inc), Javier Hernando-Ayuso (ispace, inc.)

Lunar constellation build out can is prohibitively expensive for commercial companies. This study presents a novel mission architecture which would allow lunar lander missions to deploy satellites into quasi-stable constellations at no added delta-v to their primary mission. Satellites would be deployed into elliptical lunar orbits which naturally circularize over several months to years into quasi-stable circular orbits. At their eccentricity minimum, these circular orbits can be station-kept indefinitely at approximately 10 m/s per year. Sustainable constellations can then be built out over several years to provide global lunar coverage with a focus region over the poles.

9:30 AM

AAS-118 : Direct Impulsive Transfers from Low Lunar Orbit and the Lunar South Pole to a 4:1 Southern, L2 Near-rectilinear Halo Orbit

Caleb Hernandez (Electronic Proving Ground), Davide Conte (Embry-Riddle Aeronautical University)

NASA's Artemis missions plan to return human activity back to the Moon by establishing a Lunar Orbiter and a Lunar Base Camp at the South Pole of the Moon. This paper develops a method to examine the propellant and time costs of near-optimal transfers between the Base Camp and Orbiter in the restricted three-body problem using Quantum Soliton Particle Swarm Optimization, a novel variant of the particle swarm algorithm. The resulting trajectories aid in the derivation of preliminary design requirements, such as the necessary propellant and life support systems, to accomplish the analyzed trajectories.

9:45 AM

AAS-119 : Data-Driven Summary of Continuous Thrust Trajectories in a Low-Fidelity Model of Cislunar Space

Natasha Bosanac (University of Colorado, Boulder), Maxwell Joyner (University of Colorado Boulder)

In cislunar space, a continuously thrusting spacecraft can substantially alter its path over medium and long time horizons. This paper uses clustering to automatically summarize the characteristics of the solution space for a continuously thrusting spacecraft in the Earth-Moon circular restricted three-body problem. First, the phase space is sampled in a geometry-aware manner to generate a representative set of trajectories with specified thrust directions across various spacecraft parameters. These trajectories are grouped via distributed clustering to extract their distinct types of geometries. The result is a digestible summary of the thrust-enabled solution space across an array of governing parameters.

Space Domain Awareness (SDA) and Space Surveillance I
Room: Pine, Monday, August 12
8:30 AM - 10:00 AM
Session Chair(s): Marcus Holzinger (University of Colorado Boulder) and Christopher Roscoe (Ten One Aerospace)

8:30 AM

AAS-137 : Minimum Time Reachability Metrics for Optimal Tracking of Agile Spacecraft

Casey Heidrich (University of Colorado Boulder), Marcus Holzinger (University of Colorado Boulder)

Reachability theory has important implications for operational safety and awareness in space. Full sampling of reachable sets in high-dimensional state space is computationally intractable, especially in real-time tasking operations such as optical tracking of potentially maneuvering spacecraft. Prior work has developed efficient over-approximation methods for computing spherical bounds on a reachable set, which are generally better suited for online applications. However, prior work focused on end-time fixed problems, where the final displacement is unknown. In many practical applications, the opposite problem of determining the minimum time to reach a fixed displacement is of greater interest. This work develops minimum time reachability metrics using optimal control theory with terminal displacement constraints.

8:45 AM

AAS-139 : Optical Space Domain Awareness Practical Challenges and Cost Considerations

Gavin Saul (Virginia Tech), Kevin Schroeder (Virginia Polytechnic Institute and State University)

Space Domain Awareness (SDA) is a quickly expanding field with many new government and commercial participants looking to optimize hardware for their goals while minimizing cost. Many of these new systems will take advantage of commercial off the shelf (COTS) astronomy hardware, which leads to uncertainty in how exactly a system should be designed to reach specific goals without funding bespoke hardware development. This paper will provide a literature review and modeling analysis for implementing optical SDA systems, with an emphasis on performance/cost analysis. Multiple reference systems will be presented with associated costs and recommendations for specific use cases.

9:00 AM

AAS-145 : Sun-Earth Periodic Orbit Architecture for Early Warning Asteroid Detection in Planetary Defense Mission Sets

Adam Wilmer (University of Colorado Boulder), Marcus Holzinger (University of Colorado Boulder), Michael Klonowski (University of Colorado Boulder)

The increasing concern over potentially hazardous and/or catastrophic impacts from Near-Earth objects (NEOs), such as asteroids and comets, necessitates advancements in strategies for planetary defense. This work acts to introduce a novel planetary defense orbital architecture dedicated to the detection, tracking, and characterization of NEOs. Specifically, this work will utilize Monte Carlo Tree Search (MCTS) to identify a near-optimal orbital configuration/architecture aimed at the detection and tracking of NEOs. The observer satellites will be propagated in the Sun-Earth circular restricted three-body problem (CR3BP). This architecture aims to enhance the detection of NEOs, thus contributing significantly to planetary defense efforts.

9:15 AM

AAS-199 : Concurrent Optimization of Satellite Phasing and Tasking for Cislunar Space Situational Awareness

Malav Patel (Georgia Institute of Technology), Kento Tomita (Georgia Institute of Technology), Koki Ho (Georgia Institute of Technology)

Recently, renewed interest in cislunar space spurred by private and public organizations has driven research for future infrastructure in the region. As Earth-Moon traffic increases amidst a growing space economy, monitoring architectures supporting this traffic must also develop. These are likely to be realized as constellations of patrol satellites surveying traffic between the Earth and the Moon. This work investigates the concurrent optimization of patrol satellite phasing and tasking to provide information-maximal coverage of traffic in periodic orbits.

9:30 AM

AAS-429 : Information Theoretic Trajectory Planning for Autonomous Absolute Navigation and Tracking Using Sequential Convex Programming

Trevor Wolf (The University of Texas at Austin), Brandon Jones (The University of Texas at Austin)

In our previous work, we developed a trajectory planning for a low-thrust sensing platform designed to maintain an orbit determination solution for one or multiple targets operating in the cislunar domain. This work extends these results by relaxing the assumption that the observer's state is perfectly known. This type of problem is colloquially referred to as Spacecraft-to-Spacecraft Absolute Tracking (SSAT). Like our previous work, we use mutual information as an objective function in a direct collocation scheme, however, the state of the system is now augmented by the state of the observer itself.

9:45 AM

AAS-252 : Cislunar Space Domain Awareness Leveraging Resonant Tori Structures

Ian Down (Texas A&M University), Kyle DeMars (Texas A&M University), Manoranjan Majji (Texas A&M University, College Station)

Optical sensor spacecraft are phased on 2-dimensional quasi-periodic invariant tori grown from Earth-Moon resonant orbits to track uncooperative targets in various cislunar orbital regimes. Target illuminance and celestial body occulusion are included in the analysis. An unscented Kalman filter and nonlinear particle filter are developed and compared in their ability to track targets. Particular attention is paid to initializing the target's state uncertainty distribution through Fisher information using a minimal amount of generated data. Conclusions are drawn about ideal longitudinal and latitudinal phasing of sensors on the torus surface to maximize domain coverage.

Spacecraft Guidance, Navigation and Control (GNC) I
Room: Centennial E , Monday, August 12
8:30 AM - 10:00 AM
Session Chair(s): Roberto Armellin (Te Punaha Atea - Space Institute, The University of Auckland) and Anubhav Gupta (In Orbit Aerospace, Inc. & University of Colorado Boulder)

8:30 AM
AAS-122 : High-Precision Formation Flight Navigation and Control System with Optical Laser Sensors
Tomoki Mochizuki (The University of Tokyo), Satoshi Ikari (The University of Tokyo), Shinichi Nakasuka (The University of Tokyo)

In recent years, there has been a growing interest in the high-precision Formation Flight (FF) control technology for high-resolution telescopes and interferometry missions in space. The successful realization of such missions hinges upon the maintenance of relative positions and attitudes within the prescribed mission requirements, especially within an accuracy ranging from mm to $\textmu$m. To attain the requisite precision in the relative position and attitude determination, this paper proposed an optical laser sensors named the Quadrant Photodiode Sensor (QPS) system, and showed the position determination accuracy with the QPS system.

8:45 AM
AAS-138 : Autonomous Burn Targeting for a Lunar Sortie Staged from a Near-Rectilinear Halo Orbit
Greg Dukeman (NASA), Will Krolick (NASA)

NASA is planning manned lunar landings starting in the mid 2020s as part of its Artemis program. These lunar sortie missions will be staged from a Near-Rectilinear Halo Orbit (NRHO), with a requirement for the lander to autonomously determine the timing and targets for multiple burns so that it can navigate its way back to the staging vehicle in the NRHO. The lander mission profile transitions through multiple gravitational regimes. Options for autonomous guidance and targeting logic for each of several major maneuvers of the lunar sortie are described and demonstrated numerically in closed-loop trajectory simulations.

9:00 AM
AAS-166 : Optimal Strip Attitude Command of Earth Observation Satellite using Differential Dynamic Programming
Seungyeop Han (Georgia Institute of Technology), ByeongUn Jo (Georgia Institute of Technology), Koki Ho (Georgia Institute of Technology)

This paper addresses the optimal scan profile problem for strip imaging in an Earth observation satellite (EOS) equipped with a time-delay integration (TDI) camera. Modern TDI cameras can control image integration frequency during imaging operation, adding an additional degree of freedom (DOF) to the imaging operation. On the other hand, modern agile EOS is capable of imaging non-parallel ground targets, which require a substantial amount of angular velocity and angular acceleration during operation. We leverage this DOF to minimize various factors impacting image quality, such as angular velocity and angular acceleration.

9:15 AM

AAS-167 : Time Efficient Rate Feedback Tracking Controller with Slew Rate and Control Constraint

Seungyeop Han (Georgia Institute of Technology), ByeongUn Jo (Georgia Institute of Technology), Koki Ho (Georgia Institute of Technology)

This paper proposes a time-efficient attitude-tracking controller considering the slew rate constraint and control constraint. The algorithm defines the sliding surface, which is the summation of command, body, and regulating angular velocity, and utilizes the sliding surface to derive the control command that guarantees finite time stability. The regulating rate, which is an angular velocity regulating the attitude error between the command and body frame, is defined along the instantaneous eigen-axis between the two frames to minimize the rotation angle. In addition, the regulating rate is shaped such that the slew rate constraint is satisfied while the time to regulation is minimized with consideration of the control constraint.

9:30 AM

AAS-170 : Spacecraft Dynamics Containing Prescribed Motion Platforms with Dynamic Sub-Components

Leah Kiner (University of Colorado Boulder), Hanspeter Schaub (University of Colorado)

The ability to model, simulate and analyze complex spacecraft designs is crucial to verify mission requirements and ensure the long-term success of space missions. Previous work formulated the dynamics for spacecraft designs consisting of N attached rigid bodies following prescribed motion relative to a rigid spacecraft hub. This work develops the new ability to simulate branched spacecraft components, where N rotating sub-components can be directly attached to a hub-connected prescribed motion element. The dynamics of this general system are derived and implemented using the backsubstitution formulation. The applicability of this development is demonstrated using a multi-body solar array deployment scenario.

Trajectory, Mission, and Maneuver Design/Optimization I
Room: Centennial F, Monday, August 12
8:30 AM - 10:00 AM
Session Chair(s): Vishala Arya (Jet Propulsion Laboratory) and David Spencer (The Aerospace Corporation)

8:30 AM
AAS-128 : Mission Planning and Trajectory Design of Roundtrip Mars Transfers
Min Qu (AMA), Patrick Chai (NASA Langley Research Center)

The National Aeronautics and Space Administration's (NASA's) Exploration Systems Development Mission Directorate (ESDMD) has been developing architecture concepts for human missions to Mars, and one of the key components is the in-space transportation system that delivers crew and cargo to Mars vicinity and returns the crew safely back to Earth. The Mars Architecture Team (MAT) within ESDMD's Strategy and Architecture Office has been running a large number of trade studies on different in-space transportation architecture options of two major categories: hybrid and high thrust transportation systems. This paper documents the tools and methods used to perform mission scans for systems that use high thrust propulsion.

8:45 AM
AAS-129 : UMPIRE: Universal Mission Planner to Investigate Refueling Effectiveness
Nate Wilson (Orbit Fab)

UMPIRE is a mission planning tool used by the Mission Analysis and Business Development teams to perform refueling studies and plan on-orbit architecture and spacecraft. Satellites are currently designed with a single fuel tank that once expended, signals the end of the mission. Refueling changes that paradigm, allowing missions and lifetimes to be governed by avionics, not fuel expenditure. This spawns unique opportunities for satellite operators to pursue bigger and bolder missions. However, gauging exactly what those new opportunities are is a lengthy, iterative process requiring significant planning and engineering. To solve this problem, Orbit Fab has created UMPIRE.

9:00 AM
AAS-130 : Analytical optimization of post mission disposal maneuvers towards an earth re-entry with averaged dynamics models
Xiaodong Lu (Politecnico di Milano), Camilla Colombo (Politecnico di Milano)

This research focuses on design of post mission disposal of a spacecraft in highly elliptical orbits through an Earth re-entry. Natural perturbations could be enhanced by impulsive maneuvers, which moves a spacecraft to a trajectory naturally evolving towards an Earth re-entry. The triple averaged Hamiltonian is used to describe the dynamics and the Lagrangian multipliers are computed as closed form. The obtained results are not as accurate as the ones obtained from optimization with numerical propagation due to elimination of the node, but the computational time is reduced a lot.

9:15 AM
AAS-178 : Adaptive Cover Scheme Methods Applied to Solving Optimal Control Problems in Space Flight Applications
Bethany Hintz (University of Central Florida), Tarek Elgohary (University of Central Florida)

In this work, an adaptive collocation method using cover schemes and local collocation to solve nonlinear optimal control problems that require longer integration times is presented. First, the necessary conditions of optimality are derived and then cast into a two-point boundary value problem (TPBVP) approximated using Coupled Radial Basis Functions (CRBFs). Local collocation is achieved by dividing the domain of the problem into covers. The covers can overlap and share multiple nodes, which reinforce continuity. The method is demonstrated by solving a simple pendulum problem as a proof of concept before extending to Lambert's problem and a low thrust orbital transfer problem.

9:30 AM
AAS-213 : Learning Optimal Control and Dynamical Structure of Global Trajectory Search Problems with Diffusion Models
Jannik Graebner (Princeton University), Anjian Li (Princeton University), Amlan Sinha (Princeton University), Ryne Beeson (Princeton University)

Spacecraft trajectory design is a global search problem where previous work has revealed specific solution structures that can be captured with data-driven methods. This paper explores two global search problems in the circular restricted three-body problem: hybrid cost function of minimum fuel/time-of-flight and transfers to energy-dependent invariant manifolds. These problems display fundamental structure either in the optimal control profile or the use of dynamical structures. We build on our prior generative machine learning framework to apply diffusion models to learn the conditional probability distribution for the search problem and also analyze the model's capability to capture these fundamental structures.

9:45 AM
AAS-233 : Solving Finite Thrust Optimal Control Problems Using Reachable Sets
Prashant Patel (Institute for Defense Analyses), Daniel Scheeres (University of Colorado Boulder)

Reachable sets encode information about all the achievable trajectories. This implies that a single reachable set can also can be used to solve a wide range of optimization problems such as minimum time or minimum fuel problems. One challenge is extracting this information from point cloud representations of reachable sets. This paper shows how information from reachable sets can be used to solve various optimal control problems. In addition, the paper demonstrates that the solution to these problems also allows us to estimate the control law to the desired orbit. The approach outlined in the paper works for both indirect and direct formulations and does not require an initial guess.

Trajectory, Mission, and Maneuver Design/Optimization II
Room: Centennial F, Monday, August 12
10:30 AM - 12:30 PM
Session Chair(s): Angela Bowes (NASA LaRC) and Matthew Shaw (Lockheed Martin Corporation)

10:30 AM
AAS-109 : A Feedback Guidance Law for Multi-Revolution Planetocentric Orbital Maneuvering of Solar Sail Spacecraft
Mingde Yin (University of Toronto), Christopher Damaren (University of Toronto Institute for Aerospace Studies)

A two-stage solar sail guidance law for planetocentric orbital transfers is developed, adapting the highly successful Q-Law. The first stage uses a Q-Law which is agnostic of solar sail dynamics, producing an "ideal" thrust direction which is then altered by a heuristic-based second stage to enforce cone angle limits. Although it relaxes the Lyapunov stability of the Q-Law, testing has yielded convergence in complex multi-revolution transfers involving large changes in orbital elements. The robustness of the underlying Q-Law and the minimal dependence on sail characteristics make this combined law suitable for developing new solar sail dynamics and mission designs.

10:45 AM
AAS-142 : Tri-Elliptic Aero-Assisted Orbit Transfers Between Coplanar Orbits
Eric Butcher (University of Arizona)

In this paper the previously studied bi-elliptic aero-assisted orbit transfer between coplanar circular or elliptic orbits with two impulsive maneuvers is extended to include three elliptic segments with three tangential impulsive maneuvers, the first of which raises the apoapsis similar to the reversible bi-elliptic orbit transfer. In the limit where the apoapsis goes to infinity the parabolic aero-assisted transfer is obtained. The conditions where the tri-elliptic transfer uses less fuel than the bi-elliptic aero-assisted transfer are obtained, and delta-v comparisons with the Hohmann and reversible bi-elliptic transfers to the same apoapsis radius are also provided.

11:00 AM
AAS-153 : Probabilistic Trajectory Design via Approximate Gaussian Mixture Steering
William Fife (Texas A&M University), Kyle DeMars (Texas A&M University), Pradipto Ghosh (Johns Hopkins University Applied Physics Lab)

A method is presented to solve a stochastic, nonlinear optimal control problem representative of spacecraft trajectory design under uncertainty. The problem is formulated as a chance constrained distribution steering problem. Typical distribution steering problems rely on the underlying uncertainties to be Gaussian distributions. This work expands on previous developments by embedding Gaussian mixture distributions into the formulation to better handle the uncertainty propagation and chance constraints involved. The method is applied to a finite-thrust Earth-to-Mars transfer problem. Evaluation via Monte Carlo analysis shows a greater satisfaction of constraints under non-Gaussian distributions of the state and a statistically lower cost.

11:15 AM
AAS-158 : Recovery from Missed Thrust During Low Thrust Insertion of NASA's Gateway into a Near

Rectilinear Halo Orbit
Scott Karn (NASA Glenn Research Center), Steven McCarty (NASA Glenn Research Center), Melissa McGuire (NASA GRC)

Strategies are assessed by which the first two elements of Gateway could recover from missed thrust events during insertion into a Near Rectilinear Halo Orbit (NRHO). Recovery strategies are assessed in terms of their ability to maintain the desired NRHO insertion epoch, their cost in terms of additional time required to reach the NRHO, Δv, and propellant required. Results cover the use of a chemical reaction control system as well as a 50kW ion propulsion system. Recovery solutions are found which, in the event of missed thrust, deliver the spacecraft to the NRHO within two additional revolutions and less than 80 m/s.

11:30 AM
AAS-161 : Generating the trajectory design space for Neptunian system exploration
Giuliana Elena Miceli (University of Colorado Boulder), Natasha Bosanac (University of Colorado, Boulder), Reza Karimi (NASA-JPL)

This paper uses a motion primitive approach to explore regions of a trajectory trade space for a spacecraft in the Neptunian system. First, motion primitives are generated to supply a subset of building blocks for constructing complex trajectories. A graph is then constructed to represent the potential for these primitives to be connected while satisfying path, mission, and hardware constraints. Searching this graph produces an array of geometrically distinct initial guesses. After corrections and optimization, the result is a rapidly generated tradespace of constrained transfers from a high-energy interplanetary arrival condition to various orbits that support scientific observations.

11:45 AM
AAS-163 : An Exact Solution to Lambert's Problem
Aimar Negrete (Iowa State University), Ossama Abdelkhalik (Iowa State University)

The solution to Lambert's problem is one of the fundamental problems in astrodynamics and space trajectory optimization. Since its inception, many different formulations and algorithms have been developed to solve this problem. In this work, an exact solution to Lambert's problem is derived in terms of complex contour integrals by extending the transfer time function defined in terms of the universal variable into the complex plane. A family of contours is selected and numerical quadrature is used to approximate the resulting integrals. A Monte Carlo analysis on the elliptic test case demonstrates the numerical precision of the method.

12:00 PM
AAS-164 : Comparing Relative Reachable Sets About Nearly Circular Orbits
Jackson Kulik (Cornell University), Dmitry Savransky (Cornell University), Maxwell Zweig (Cornell University)

The relative reachable set problem considers the set of positions or states that are reachable at a given time under constraints on control authority. Some formulations of constraints on control authority lead to analytically tractable computations of the reachable sets while others are more directly applicable to real-world spacecraft operations. We will compare different formulations of the relative reachable set problem and analyze the approximation quality of an impulsive reachable set as a stand-in for a constant-thrust reachable set and an energy-limited reachable set as a proxy for a thrust-limited reachable set.

Cislunar Astrodynamics II
Room: Pinon, Monday, August 12

10:30 AM - 12:30 PM
Session Chair(s): Diane Davis (NASA Johnson Space Center) and Smriti Nandan Paul (Missouri University of Science and Technology)

10:30 AM
AAS-133 : Abort Trajectory Design Strategies for the Artemis Missions
Brian McCarthy (a.i. solutions, Inc), Joshua Geiser (NASA Johnson Space Center), Daniel Owen (Advanced Space), Matthew Bolliger (Advanced Space)

NASA's Artemis campaign plans to send astronauts to the lunar surface for the first time since 1972. The campaign relies on the Orion capsule to ferry the crew to an L2 9:2 lunar synodic resonant Near-Rectlinear Halo Orbit (NRHO) before descent to the lunar surface. This investigation examines a methodology to construct various abort families during transit from Earth to the NRHO using the Earth-Moon Circular Restricted Three-Body Problem (CR3BP). A process is then summarized to transition trajectories from the CR3BP into a higher-fidelity model. Ultimately, development, classification, and convergence of aborts in higher-fidelity is critical to the Artemis program in the event of an anomaly during the crew transit.

10:45 AM
AAS-160 : Orthogonal Integral Collocation Techniques for Solutions of Problems of Variational Mechanics
Thomas Ahrens (Texas A&M University), Manoranjan Majji (Texas A&M University, College Station), John L. Junkins (Texas A&M University)

Variational mechanics formulations are utilized to approximate the path of dynamical systems that minimize a Lagrangian functional. By parameterizing the velocity and acceleration of a dynamical system as an orthogonal series, the paper derives the necessary functions to determine the coefficients that extremalize the variational cost function associated with the Lagrangian. The resulting transversality conditions lead to the necessary conditions for initial and boundary value problems. The use of the variational method to accommodate the costs associated with the control functions are demonstrated. Trajectories in multi-body gravitational environments are computed to demonstrate the utility of the formulations involved.

11:00 AM
AAS-171 : The Inclined Hill Restricted Four-Body Problem : Derivation and Applications
Adrien Legrand (University of Colorado Boulder), Daniel Scheeres (University of Colorado Boulder)

The Hill restricted four-body problem is a time-periodic, dynamically coherent model generalizing both the restricted and the Hill three-body problem. It takes a particular analytical solution for the relative motion of the primaries, but assumes coplanar motion of the 3 massive bodies, something in general not accurate. In this work, we introduce inclination of the primaries by adding to it an out-of-plane componen, obtained by linearization of the equations of motion, to form the Inclined Hill Restricted Four-Body Problem. Numerical investigation of the dynamical structures existing in the system is carried out, focusing on the equivalents to the Lagrange points.

11:15 AM
AAS-185 : Low Energy Transfer to Lunar Orbit Using Small Solar Sails
Kohei Oue (Tokyo Institute of Technology), Toshihiro Chujo (Tokyo Institute of Technology), Hiroki Nakanishi (Tokyo Institute of Technology)

This paper presents a trajectory design of low energy transfers from Earth to Lunar orbit using small solar sail spacecraft equipped with solar electric propulsion system. Lunar swing-by conserves propellant during the transfer, but its window is narrow, particularly for piggyback small spacecrafts. We propose a trajectory optimization process for solar sails that leverages both weak stability boundary effect and solar radiation pressure to reduce propellant consumption and expand the swing-by window compared to conventional transfers. In numerical examples, we analyze transfers for one year and clarify to what extent solar sails reduce propellant, and show some propellant-free transfers.

11:30 AM
AAS-204 : Behavior of the Lunar Gateway's Planned Orbit in the Sun-Earth-Moon System
Gavin Brown (University of Colorado Boulder), Luke Peterson (University of Colorado Boulder), Damennick Henry (University of Colorado at Boulder), Daniel Scheeres (University of Colorado Boulder)

The Earth-Moon L2 9:2 NRHO is a periodic orbit in the CR3BP representing the lunar Gateway's planned orbit. Accounting for the effect of the Sun can change the behavior of periodic orbits. We pair Melnikov theory with a continuation algorithm to transition this orbit into a Sun-Earth-Moon restricted 4-body problem (SEM R4BP). There is not a singular 9:2 NRHO in the SEM R4BP, rather there are many—numerically foliating a 2D torus. This behavior is unexpected, so we consider other resonant periodic orbits and multiple dynamical models, and find this behavior present.

11:45 AM
AAS-206 : Investigation of Low-Thrust Enabled State-Return Trajectories in the CR3BP
Colby Merrill (Cornell University), Jackson Kulik (Cornell University), Dmitry Savransky (Cornell University)

In this work, we investigate state return trajectories that require thrust in the circular-restricted three body problem (CR3BP). The most well-studied state-return trajectories are the periodic structures in the CR3BP. Although these structures are naturally periodic in the CR3BP, spacecraft operating in orbit require stationkeeping to maintain these orbits under a higher-fidelity force model. Similar to this, we study forced state-return trajectories using the linearized model of energy optimal control around naturally periodic orbits with the goal of expanding orbit options for spacecraft.

12:00 PM
AAS-210 : Modeling and Phasing Considerations for Near Rectilinear Halo Orbit Baselines
Emily Zimovan-Spreen (NASA Johnson Space Center), Diane Davis (NASA Johnson Space Center), Brian McCarthy (a.i. solutions, Inc)

A Near Rectilinear Halo Orbit (NRHO) with an eclipse-favorable phase serves as the current baseline orbit for the Gateway mission. The baseline provides a catalog of orbit maintenance targets and serves as a reference path for other types of trajectory analysis. In this investigation, effects of higher-fidelity modeling on NRHO baselines are studied. Monte Carlo analysis illustrates orbit maintenance costs with various baseline and propagation model combinations. Additionally, two 20-year-duration 9:2 NRHO baselines in different eclipse-avoidant phases are compared geometrically and within the context of orbit maintenance costs.

12:15 PM
AAS-211 : Defining Linear Operators in the Circular-Restricted Three-Body Problem using Least Squares
Shantanu Trivedi (Purdue University), David Arnas (Purdue University)

This work proposes a methodology to obtain a linear Koopman operator able to represent the non-linear dynamics characteristic of the Circular-Restricted Three-Body Problem. This methodology is applied to the motion about the libration points and allows generating a a semi-analytical approximate solution of the system that can be used for different applications, including orbital propagation and the study of the dynamical properties of the system. The proposed technique is based on a least squares method to approximate the non-linear dynamics into a finite linear system of basis functions. Additionally, applications of this technique to relative motion and optimal control along with the limits of this method are also discussed.

Spacecraft Guidance, Navigation, and Control (GNC) II
Room: Centennial E , Monday, August 12
10:30 AM - 12:30 PM
Session Chair(s): Simone Servadio (Iowa State University)

10:30 AM
AAS-174 : Guidance and Control of Formation Flying Reconfiguration Considering Collision Avoidance in the CRTBP
Hirotaka Sekine (The University of Tokyo), Yosuke Kawabata (The University of Tokyo), Kenshiro Oguri (Purdue University), Ryu Funase (The University of Tokyo)

In recent years, many formation flying missions have been proposed in the circular restricted three-body problem. Among these missions, reconfiguration in relative positions between satellites is essential. This is particularly critical when the distance between satellites is minimal, such as only a few hundred meters, requiring collision avoidance. This study proposes the use of a chance-constrained model predictive control for formation reconfiguration, demonstrating its effectiveness in probabilistically managing collision risks. Furthermore, it suggests employing quasi-periodic tori for changes in the inertial-pointing observation direction, showing that this approach can facilitate formation reconfigurations that maintain inter-satellite distances while reducing fuel consumption.

10:45 AM
AAS-190 : Stereo Thermoclinometry (STC): A Method to Characterize Small Body Shapes using Infrared Images
Koundinya Kuppa (University of Colorado, Boulder), Jay McMahon (CCAR (Colorado Center for Astrodynamics Research)), Ann Dietrich (The Charles Stark Draper Laboratory)

Accurate shapes are vital to robust navigation efforts in the proximity of asteroids. Currently, Stereo Photoclinometry (SPC) is used to derive an accurate shape models from optical images but at a high computational cost. We propose a computationally efficient algorithm called Stereo Thermoclinometry (STC) to derive accurate shape models of asteroids. The algorithm uses IR images in conjunction with a Thermo-Physical Model (TPM) to update an initial shape model of an asteroid. To demonstrate the algorithm, it is applied to update the shape model of a spherical asteroid that contains a crater. STC shape model shows a 64% improvement in errors.

11:00 AM
AAS-192 : Control of the Lunar Reconnaissance Orbiter Reaction Wheel Angular Momentum Using Attitude Holds
Toni Deboeck (KBR Government Solutions / NASA GSFC), Julie Halverson (NASA GSFC), Yohannes Tedla (KBR Government Solutions / NASA GSFC)

The Lunar Reconnaissance Orbiter (LRO) uses four Reaction Wheel Assemblies (RWA) for controlling spacecraft attitude in Lunar orbit. LRO periodically performs momentum unloads by firing thrusters to reduce RWA angular momentum. Unloads are the principal source of fuel use. Off nadir attitude holds change the direction of the external torques (gravity gradient and solar pressure) in the spacecraft body frame. Processes for controlling RWA angular momentum using attitude holds were developed. These processes require evaluation of numerous spacecraft, ground, and science instrument constraints. Using momentum attitude holds is projected to extend LRO fuel lifetime by several years.

11:15 AM
AAS-203 : Probabilistic Spacecraft Landing in Hazardous Terrain on Small Bodies
Zachary Donovan (University of Colorado Boulder), Jay McMahon (CCAR (Colorado Center for Astrodynamics Research))

The irregular geometry and complex dynamic environments of small planetary bodies makes them challenging targets for a spacecraft landing. Large curvature and erratic terrain cause the typical assumptions for landing dispersion characterization to break down. A weak gravitational field further exacerbates unpredictable behavior in the spacecraft's trajectory after touchdown. For these reasons, a new probabilistic characterization of spacecraft landing is necessary. This paper discusses the formulation of a statistical metric for quantifying the safety of a spacecraft's landing on an asteroid's surface. This metric is then used as a steering factor to minimize hazardous landing on small planetary bodies.

11:30 AM
AAS-223 : Object Identification in Celestial Images for Autonomous Lost-in-Space Navigation
Sebastien Henry (Georgia Institute of Technology), John Christian (Georgia Institute of Technology)

Future space missions will require increasing levels of autonomy. When lost-in-space, a spacecraft can autonomously recover its state by the use of line of sights (LOS) to stars and planets. Although several works have proposed ways to estimate the state of a spacecraft using such measurements, most have assumed that these measurements are readily available with planet or other objects already identified. However, associating pixel measurements to objects is non-trivial when lost-in-space. This paper addresses the identification of planets from raw celestial images, assuming no a-priori knowledge on the spacecraft attitude and position.

11:45 AM
AAS-232 : AI based Fusion of Visible and Thermal images for robust feature extraction for Autonomous Navigation of Spacecraft Missions to Asteroids
Iain Hall (The University of Strathclyde), Jinglang Feng (University of Strathclyde), **Hao Peng** (Embry-Riddle Aeronautical University), Massimiliano Vasile (University of Strathclyde, Department of Mechanical & Aerospace Engineering)

Missions to visit asteroids depend on autonomous navigation systems to carry out operations. The extraction of features for the estimation of the relative position and attitude (pose) of the asteroid is a key step but can be challenging in the poor illumination conditions which can occur for asteroids. We explore how data fusion using machine learning can potentially allow for more robust feature extraction. Different levels of fusing visible images and thermal images using Convolutional Neural Networks are developed and tested using synthetic images based on ESA's Hera mission scenario.

12:00 PM
AAS-241 : Higher-Order Analytical Efficient Covariance Analysis for Aerocapture
Grace Calkins (University of Colorado Boulder), David Woffinden (NASA Johnson Space Center), Jay McMahon (CCAR (Colorado Center for Astrodynamics Research))

This paper presents an analytical approach for uncertainty quantification in aerocapture scenarios. Combining higher-order directional state transition tensors and Gaussian mixture models, the proposed method seeks to efficiently propagate uncertainties and represent highly nonlinear terminal distributions. Directional state transition tensors are used to determine the direction of mixand splitting and improve computational efficiency in covariance propagation. As an example, the Uranus Orbiter Probe mission aerocapture scenario is analyzed with the proposed analytical method and results are compared to Monte Carlo simulations.

12:15 PM

AAS-243 : Grimorium Verum: On the Practice of BLACMAGIC for Simulation of Ground Tracking Performance in Orion GN&C Testing

Kari Ward (The Charles Stark Draper Laboratory), Christopher D'Souza (NASA - Johnson Space Center), Greg Holt (NASA Johnson Space Center)

The Orion onboard navigation nominal concept of operations hinges upon periodic ground state updates (GSUs) to reset one or more navigation filters' state estimates and associated covariance with a more accurate solution. In flight, these states and covariances are taken from filtering of tracking data provided by the Deep Space Network. In simulation however, it is necessary to model these covariances with a less computationally intensive process. The Batch Like Approximate Covariance for the Modeling of Artemis Ground Induced Commands (BLACMAGIC) algorithm computes this covariance given the vehicle inertial position and velocity at the time of interest for the GSU.

SPECIAL SESSION: Astrobotic Peregrine
Room: Pine, Monday, August 12
10:30 AM - 12:30 PM
Session Chair(s): Brian Gunter (Georgia Institute of Technology)

10:30 AM

AAS-420 : Astrobotic Peregrine Mission One: Pre-Launch Mission Design and Analysis

Michael Lachenmann (Astrobotic), Dan Junker (Astrobotic), Alexander Hoffman (Astrobotic), **John Carrico** (Space Exploration Engineering, LLC), JP Carrico (Space Exploration Engineering, LLC), Craig Nickel (Space Exploration Engineering), Alisa Hawkins (Space Exploration Engineering (SEE)), Tom Garvey (Astrobotic)

Astrobotic's Peregrine Mission 1 (PM1) was the first successful launch of a com-mercial US Moon lander under NASA's Commercial Lunar Payload Services in-itiative. This paper gives an overview of the trajectory design and some of the design choices that were made. It then describes the flight dynamics pre-launch analysis that went into this mission. This included a launch period analysis that determined the feasible launch days, a launch window analysis that determined the launch instances on a given day, and a Monte Carlo analysis, that determined the sensitivity of various parameters for a given launch instance.

10:45 AM

AAS-422 : Astrobotic Peregrine Mission One: Pre-Launch Orbit Determination Analysis

JP Carrico (Space Exploration Engineering, LLC), **John Carrico** (Space Exploration Engineering, LLC), Michael Lachenmann (Astrobotic), Craig Nickel (Space Exploration Engineering), Alexander Hoffman (Astrobotic), Lisa Policastri (Space Exploration Engineering, LLC)

Astrobotic's Peregrine Mission One was planned to be one of the first landers to return a U.S.A. presence back to the lunar surface. The design reference mission for Peregrine Mission One included a series of maneuvers for orbit correction, lunar orbit insertion, and orbit-lowering, and included requirements imposed by the Powered Descent phase of the mission, as well as other constraints. The impact of these mission requirements on the orbit determination plan is discussed, as well as the subsequent analyses that defined and validated the orbit determination plan against these requirements for each phase of the mission.

11:00 AM

AAS-413 : Astrobotic Peregrine Mission One: Flight Dynamics System

JP Carrico (Space Exploration Engineering, LLC), **Craig Nickel** (Space Exploration Engineering), Alisa Hawkins (Space Exploration Engineering (SEE)), John Carrico (Space Exploration Engineering, LLC), Michael Lachenmann (Astrobotic), Alexander Hoffman (Astrobotic)

On January 08, 2024, Astrobotic's Peregrine Mission One became the first US commercial lunar lander to operate in space. Despite a debilitating propulsion sys-tem anomaly in the early hours after launch, the mission lasted ten days and reached lunar distance before ultimately entering the Earth's atmosphere. This document describes the design and implementation of the Flight Dynamics Sys-tem used by the flight dynamics team both pre-launch and during operations. Au-tomation of many flight dynamics operational processes was essential to reliably generate and deliver products to keep up with the fast-paced nature of the mission and respond to challenges that arose.

11:15 AM

AAS-412 : Astrobotic Peregrine Mission One: Flight Dynamics Operations, Challenges, and Successes

Michael Lachenmann (Astrobotic), John Carrico (Space Exploration Engineering, LLC), JP Carrico (Space Exploration Engineering, LLC), Alisa Hawkins (Space Exploration Engineering (SEE)), **Alexander Hoffman** (Astrobotic), Craig Nickel (Space Exploration Engineering), Tom Garvey (Astrobotic)

Astrobotic's Peregrine Mission One (PM1) was the first successful launch of a commercial US Moon lander under NASA's Commercial Lunar Payload Ser-vices initiative. This paper gives an overview of the challenges encountered and successes achieved by the Flight Dynamics team throughout the mission's opera-tional phase. After a mission ending failure shortly after separation, the team had to adapt and develop new processes and tools in real time. The S/C failure caused the S/C to eventually re-enter the Earth's atmosphere after 10 days in a highly excentric orbit. Several short maneuvers were performed to control the re-entry location and steer it to an uninhabited area in the Pacific Ocean.

11:30 AM

AAS-419 : Astrobotic Peregrine Mission One: Orbit Determination Operations

JP Carrico (Space Exploration Engineering, LLC), **Craig Nickel** (Space Exploration Engineering), Alisa Hawkins (Space Exploration Engineering (SEE)), Michael Lachenmann (Astrobotic), Alexander Hoffman (Astrobotic), John Carrico (Space Exploration Engineering, LLC)

On January 08, 2024, Astrobotic's Peregrine Mission One became the first US commercial lunar lander to operate in space. Despite a debilitating propulsion system anomaly in the early hours after launch, the mission lasted ten days and reached lunar distance before ultimately entering the Earth's atmosphere. This paper describes the orbit determination operations for Peregrine, detailing the challenges faced to track and predict the satellite state, and the operational solu-tions to these challenges. These challenges were primarily caused by the propulsion system anomaly, however other operational issues compounded the flight dynamics operations.

11:45 AM

AAS-418 : Astrobotic Peregrine Mission One: Retrospective Analysis of Optical Observations

JP Carrico (Space Exploration Engineering, LLC), John Carrico (Space Exploration Engineering, LLC), Alexander Hoffman (Astrobotic), Craig Nickel (Space Exploration Engineering), Michael Lachenmann (Astrobotic), Max Geissbuhler (Slingshot Aerospace), Thomas Johnson (Exa Research, LLC), Alex Ferris (Numerica Corporation)

As part of the NASA Commercial Lunar Payload Services program, Astrobotic's Peregrine Mission One was planned to land a vehicle on the moon. During operations optical observations were obtained from the amateur astronomy community, including the Project Pluto collaborators, as well as the commercial optical tracking network, Slingshot Aerospace. During operations these observations were incorporated into non-operational, "shadowing" solutions that were used to gain confidence in the primary, definitive solution. This paper retrospectively provides examines the observability of the covariance to these measurements, as well as the consistency of sequential orbit predictions under combinations of tracking data sources.

12:00 PM

AAS-415 : Astrobotic Peregrine Mission One: Modeling Anomaly Perturbations

Alisa Hawkins (Space Exploration Engineering (SEE)), John Carrico (Space Exploration Engineering, LLC), Craig Nickel (Space Exploration Engineering), JP Carrico (Space Exploration Engineering, LLC), Michael Lachenmann (Astrobotic), Alexander Hoffman (Astrobotic)

On January 08, 2024, Astrobotic's Peregrine Mission One launched on a Vulcan Rocket and then separated after Translunar Lunar Injection. Shortly afterwards a propulsion system leak occurred causing a strong torque on the lander. The control system reacted by constantly firing the reaction thrusters. The combined force from the leak and the thruster caused strong perturbations on the trajectory. We describe the techniques used to track and estimate the orbit during operations ac-counting for the changing force. We also describe the method used to predict the trajectory well enough to maneuver to a desired location in the Pacific Ocean.

12:15 PM

AAS-411 : Astrobotic Peregrine Mission One: Earth Entry: Location Prediction, Monte Carlo Analysis, and Correction Maneuver Planning

Alexander Hoffman (Astrobotic), Michael Lachenmann (Astrobotic), JP Carrico (Space Exploration Engineering, LLC), Alisa Hawkins (Space Exploration Engineering (SEE)), John Carrico (Space Exploration Engineering, LLC), Craig Nickel (Space Exploration Engineering)

On January 08, 2024, Astrobotic's Peregrine Mission One became the first US commercial lunar lander to operate in space. Despite a debilitating propulsion system anomaly in the early hours after launch, the mission lasted ten days and reached lunar distance before ultimately entering the Earth's atmosphere. This document focuses on the flight dynamics analyses conducted over the last few days of the mission to safely execute a controlled Earth entry, including prediction of entry location incorporating spacecraft venting disturbances, Monte Carlo analysis, and maneuver planning to adjust the Earth entry location. The insights gained to successfully processes, challenges, and perform an unplanned atmospheric entry are described.

Attitude Dynamics, Determination, and Control I
Room: Centennial E , Monday, August 12
2:00 PM - 3:15 PM
Session Chair(s): Davide Guzzetti (Auburn University) and Heather Koehler (NASA NESC)

2:00 PM

AAS-101 : Discrete Time Indirect Adaptive Control Stabilized by A zero Placement Algorithm Using Multiple Zero Order Holds

Jer-Nan Juang (National Cheng Kung Univ), Richard Longman (Columbia University), **Joseph Fritch** (Columbia University)

Recent research by the authors created an algorithm to perform zero placement on digital systems using multiple zero order hold inputs between the original addressed zero error time steps. In order to improve on this performance one would like to make adaptive updates of the model. The adaptive zero placement algorithm now makes it possible to create digital models of general discrete time systems that have a stable inverse. It is the purpose of this paper to examine the combination of the stabilizing zero placement algorithm and discrete time adaptive control. The approach is applied to a spacecraft consisting of a hub and two flexible appendages.

2:15 PM

AAS-262 : Efficient Onboard Attitude Commanding for Fast Maneuvering of Lunar Reconnaissance Orbiter

Mark Karpenko (Naval Postgraduate School), Joshua Levitas (Naval Postgradaute School), Roberto Cristi (Naval Postgraduate School), Joshua Miller, Scott Snell, Yohannes Tedla (KBR Government Solutions / NASA GSFC), Kelsey Caldwell, Julie Halverson (NASA GSFC)

To support Lunar Reconnaissance Orbiter's extended science missions, an algorithm (FastXMan) for autonomous optimization of fast occultation avoidance maneuvers was developed. Executing FastXMan requires transmission and storage of a large number of time-tagged attitude waypoints on the spacecraft. For more efficient day-to-day operations, an interpolating filter was designed to perform onboard interpolation between sparse samples of FastXMan commands. The interpolating filter was patched into LRO's flight software in late 2023 and is presently operational. This paper presents an overview of the issues related to the practical implementation of the filter and describes the flight performance of the new scheme.

2:30 PM

AAS-263 : Bilevel Attitude Guidance Optimization of Agile CMG Maneuvers

Miles Zembruski (Naval Postgraduate School), Jeffery King (Naval Postgraduate School), **Mark Karpenko** (Naval Postgraduate School)

Attitude guidance optimization can be used to design agile CMG reorientation maneuvers. For predictable tracking in the closed-loop, the CMG steering logic must be incorporated into the optimization. Full envelope CMG torque authority can be achieved by solving a static optimization problem at each control cycle. However, incorporating this constraint in attitude guidance optimization gives rise to a bilevel trajectory optimization problem where CMG steering optimization is an embedded constraint. This paper presents a new trajectory optimization problem formulation and its solutions for solving this bilevel problem. Analysis of the necessary conditions is used to validate the results.

2:45 PM

AAS-264 : Semi-Passive Zero-Knowledge Tumbling for Small Satellite Insolation Maximisation: Anti-Eigenvectors and the Dzhanibekov Effect

Kyle McMullan (Curtin University)

Attitude determination and control is often vital to ensure solar power generation systems capture enough energy for mission success. Due to the size, weight, and power constraints on small satellites, operators often turn to strategies requiring no knowledge of the satellite state in the inertial frame (referred to here as 'zero-knowledge' strategies). We show that leveraging gyroscopic torque to cause a large swept area for all satellite surfaces reduces the risk of power-related failures over detumbling. In particular, we investigate the use of angular velocities equal to the anti-eigenvectors of the satellite's inertia matrix to induce favourable tumbling.

Orbital Debris and Space Environment I

Room: Pine, Monday, August 12

2:00 PM - 3:15 PM

Session Chair(s): Vishal Ray (Kayhan Space) and David Spencer (The Aerospace Corporation)

2:00 PM

AAS-141 : Low Energy Heliocentric Disposal in a Multi-Body Framework

Edward George (The Aerospace Corporation), Joseph Gangestad (The Aerospace Corporation), Juan Maldonado (The Aerospace Corporation), Amanda Knutson (The Aerospace Corporation), Robert Potter (The Aerospace Corporation)

This paper provides the rationale and compliance guidance for a proposed update to the heliocentric-escape disposal option in the Orbital Debris Mitigation Standard Practices (ODMSP). To address missions that returned to Earth after satisfying the existing standard, the update requires vehicles to remain outside a 1,800,000-km, Earth-centered keep-out zone for 100 years. We provide quantitative justification for the definition's particulars along with a trajectory-generation methodology that empowers robust compliance without over-burdening mission design. Adoption of this updated definition will ensure that future missions align with the ODMSP's goal of preserving a safe and sustainable space environment.

2:15 PM

AAS-189 : Electrostatic Tractor Effectiveness in a Non-Maxwellian GEO Plasma Environment

Amy Haft (University of Colorado Boulder), Hanspeter Schaub (University of Colorado)

The electrostatic tractor has been proposed as a promising method to dispose of large defunct spacecraft in Geosynchronous Earth Orbit (GEO). However, suprathermal particle deviations from the Maxwellian velocity distribution function (VDF), which exist in every low-density plasma environment, may influence the controlled spacecraft charging induced by the electrostatic tractor. This paper expands on electrostatic space debris mitigation research by investigating and comparing active charging in a non-Maxwellian GEO environment using three alternate distribution models: (1) bi-Maxwellian distribution, (2) Kappa function, and (3) cool Maxwellian core with a hot Kappa halo.

2:30 PM

AAS-205 : Simulation of charge-variation-driven secular effects on sub-centimeter orbital debris clouds in response to Earth's electromagnetic field

Jonathan Wrieden (University of Maryland), Christine Hartzell (University of Maryland)

Clouds of sub-centimeter debris are generated during the orbital insertion of spacecraft into Low Earth Orbit and pose a threat to space operations but are currently undetectable by radar ground stations. Objects orbiting through space plasma become charged and experience a Lorentz force due to Earth's time-varying magnetic and electric fields. This study simulated this perturbation on a three-dimensional cloud of debris and determined that the variation in surface charging is the driving mechanism behind secular variation in orbital inclination, energy, and angular momentum, which has potential implications on debris lifespans and orbit evolution.

2:45 PM

AAS-310 : Simulating the space environment using Levy process theory based on MOCAT

Kaiqi Cui (USTC), Hou-Yuan Lin (PMO)

Concerns about the future of Low Earth Orbit (LEO) due to increasing space debris and mega-constellation projects prompt the need for advanced modeling. The MIT Orbital Capacity Assessment Tool (MOCAT) model, utilizes Ordinary Differential Equations (ODEs) to simulate the space environment dynamics. We augment it with the Monte Carlo method to address stochasticity. However, long-term simulations with MOCAT-MC lack process stability analysis. Here, we integrate MOCAT-MC with the Euler-Maruyama algorithm, enhancing precision and reducing forecasting time. We assess the stability of the space environment by analyzing stochastic differential equations. Our work offers insights into space capacity and task effects, crucial for sustainable space exploration and resource management.

Trajectory, Mission, and Maneuver Design/Optimization III

Room: Centennial F, Monday, August 12

2:00 PM - 3:15 PM

Session Chair(s): Sandeep Singh (Rensselaer Polytechnic Institute) and Rohan Sood (The University of Alabama)

2:00 PM

AAS-240 : Solar Sailing Q-Law using Keplerian Orbital Elements

Dylan LaSalle (University at Buffalo), **Grant Hecht** (University at Buffalo), Eleonora Botta (University at Buffalo)

In this paper, a Q-Law-based feedback control algorithm for a solar-sailing spacecraft in orbit around Earth is proposed. Although analytical expressions for the gradient of the candidate Lyapunov function are not available, forward-mode automatic differentiation proves useful in computing a sub-optimal control input to the system. The Keplerian parameterization of the spacecraft's orbit allows for the relaxation of key assumptions as well as intuitive targeting. Successful simulations of several orbital transfers have been completed using the proposed control algorithm, and the results help shed light on the potential usefulness of a Q-Law-based algorithm for controlling a solar-sailing spacecraft.

2:15 PM

AAS-285 : Vectorized Dynamic Size Genetic Algorithm For Fast Flyby Sequence Generation

Sungmoon Choi (Iowa State University), Ossama Abdelkhalik (Iowa State University), Ashwati Das-Stuart (Purdue University), Rodney L. Anderson (Jet Propulsion Laboratory/Caltech)

Optimizing flyby sequences for an interplanetary mission poses a significant challenge due to the unknown number of optimal flyby sequences involved. Traditional global optimization algorithms typically require a fixed number of design variables, which limits their applicability to such problems. Even when the number of flybys is determined, the sheer volume of possible combinations makes it computationally expensive to optimize each sequence. This study presents a Vectorized Dynamic Size Genetic Algorithm (VDSGA), a method aimed at efficiently generating optimal flyby sequences. VDSGA demonstrates a significant reduction in computational time for generating optimal flyby sequences.

2:30 PM

AAS-299 : Optimal multiple-target missions using convex optimization and binary integer programming

Jack Yarndley (Te Pūnaha Ātea - Space Institute, University of Auckland), Harry Holt (University of Auckland), Roberto Armellin (Te Punaha Atea - Space Institue, The University of Auckland)

The optimal design of multiple-target low-thrust rendezvous and flyby missions is extremely difficult because of the combination of spacecraft trajectory optimization with high-dimensional combinatorial problems. We present our work on combining binary integer programming and successive convex programming (SCP) to solve these types of problems. An iterative approach is proposed, where the combinatorial aspect of the problem is solved using a binary integer program followed by the optimal time schedule using adaptive-time SCP, and repeated until combinatorial convergence. This is used to find the current best solution to the Global Trajectory Optimization Competition (GTOC 12) problem.

2:45 PM

AAS-330 : Deployment of Multiple Satellites On Collision-free Orbital Trajectories For Planetary Exploration

Animesh Chakravarthy (University of Texas at Arlington), Debasish Ghose (Indian Institute of Science)

This paper presents a deployment strategy for multiple satellites used for planetary exploration. It formulates the problem of determining the deployment points of multiple satellites which are designed to move on pre-fixed orbits on a spherical manifold around the planet. The deployments are done in a given sequence by a mothership, and the solution to this problem ensures collision-free orbital trajectories and also optimizes the length of the mothership's trajectory from the initial to the last deployment point. The formulation is based on concepts from spherical geometry and is novel in the literature.

Attitude Dynamics, Determination and Control II
Room: Centennial E , Monday, August 12
3:45 PM - 5:00 PM
Session Chair(s): Davide Guzzetti (Auburn University) and Heather Koehler (NASA NESC)

3:45 PM
AAS-272 : Comparison and Enhancements of Two Stable Inverses
Joseph Fritch (Columbia University), Richard Longman (Columbia University)

Spacecraft require highly accurate tracking maneuvers. Feedback control is limited as the system response to command is dictated by the bandwidth of the control system. Therefore, such control systems never do what you asked them to do. Ideally, given a good model, one could simply insert the desired output into the model and solve for the input. Existing discrete time stable inverse methods accomplish this but sacrifice inter-sample error to do so. This paper develops a method to reduce inter-sample error and actuator saturation through constrained pre-actuation, trajectory extensions for improved precomputation and feedforward compensation, making the inverse solution practical.

4:00 PM
AAS-295 : Constrained Attitude Reorientation Maneuver of Spacecraft based on Path Planning
Daegyun Choi (University of Cincinnati), Donghoon Kim (University of Cincinnati), Hyunjae Lee (Chosun University)

Spacecraft attitude control becomes challenging in the presence of constraints for some instruments that should have certain objects in their field of view and light sensitive instruments that should avoid bright objects. This work proposes a path-planning applied spacecraft attitude maneuver considering such constraints to reach the desired attitude. Constraint-compliant attitude trajectories are computed using an enhanced potential field approach in the attitude space. Then, the control input is determined by the motion-planning process satisfying dynamic constraints in the time domain based on the attitude trajectories. Numerical simulation results demonstrate successful reorientation maneuvers without violating the constraints.

4:15 PM
AAS-324 : Attitude and Gyro Bias Estimation with Intermittent Measurements
Andrew Miller (The University of Texas at Austin), Maruthi R. Akella (The University of Texas at Austin)

This paper investigates the problem of estimating the attitude and gyro bias for spacecraft that sense, receive, and/or process their attitude information intermittently due to hardware or bandwidth constraints. The attitude measurements are modulated through a time-dependent signal that is persistently excited and the gyro measurements are available continuously, but corrupted with unknown gyro bias errors. Novel nonlinear estimators are proposed for both the attitude and gyro bias. Local convergence of the attitude and bias estimates are guaranteed for initial errors within a well defined set. Simulations of the proposed estimators are carried out to demonstrate their feasibility.

4:30 PM

AAS-440 : Adaptive Controller for Simultaneous Spacecraft Attitude Tracking and Reaction Wheel Fault Detection

Camilo Riano-Rios (Florida Institute of Technology), George Nehma (Florida Institute of Technology), Madhur Tiwari (Florida Tech)

The attitude control of a spacecraft is integral to achieving mission success. However, failures in actuators such as reaction wheels are detrimental and can often lead to an early end of mission. We propose a Lyapunov-based adaptive controller that can estimate and compensate for reaction wheels degradation simultaneously. The controller incorporates an adaptive update control law with a gradient-based term and an integral concurrent learning term that collects input-output data for online estimation of uncertain parameters. The proposed controller guarantees attitude tracking and its performance is tested through numerical simulations.

Earth Orbital and Planetary Mission Studies
Room: Pine, Monday, August 12
3:45 PM - 5:00 PM
Session Chair(s): David Canales Garcia (Embry-Riddle Aeronautical University) and Jeff Parker (Advanced Space, LLC)

3:45 PM
AAS-113 : Shape-Shifting Sailer: Entry and descent trajectories for self-foldable shape memory membranes
Joseph Ivarson (Auburn University), Davide Guzzetti (Auburn University)

Future solar sail mission concepts prescribe large sail areas and thus greater contribution to the overall mass budget. As the sail mass increases, there is an increasing opportunity cost for not utilizing the mass for additional objectives during the mission. We posit that sail transformation via shape memory polymer actuated folding will enable operators to expand the capabilities of the costly spacecraft mass with potentially little to no additional penalty. Here, we investigate the benefits and feasibility of using SMP to form drag modulating shapes that can reduce thermal loads upon re-entry.

4:00 PM
AAS-198 : Time Efficiency and Mission Duty Cycle Evolution for Observatory and Deep-Space Electric Propulsion Missions
Christopher Lawler (NASA Jet Propulsion Laboratory), Marc Rayman (Jet Propulsion Laboratory), Sarah Bairstow (NASA Jet Propulsion Laboratory), David Seal (NASA Jet Propulsion Laboratory), Sean Bryan (Arizona State University), Mike Packard (University of Colorado Laboratory for Atmospheric and Space Physics), Jeremy Knittel (Laboratory for Atmospheric and Space Physics (LASP)), Heyam Alblooshi (United Arab Emirates Space Agency)

A key operational resource for deep-space electric propulsion and observatory missions is mission duty cycle, which is the fraction of time dedicated to thrusting when required or observing, respectively. This paper presents a new dataset of time duty cycle estimates and realized values at different milestones over the lifecycles of multiple NASA projects, and integrates these data with already-published values from other missions. Project-specific factors that led to the trend seen for each mission are discussed, as well as common threads and lessons learned for future missions that require a high mission duty cycle.

4:15 PM
AAS-267 : An Autonomous PNT and Data Relay Services Architecture in Cislunar Space
Benjamin Tatman (Advanced Space), Anthony Zara, Matthew Givens (Advanced Space), Galen Savidge (Ann & H.J. Smead Department of Aerospace Engineering Sciences at CU Boulder), Sai Chikine (University of Colorado Boulder), Matthew Bolliger (Advanced Space)

The authors propose a novel architecture for autonomous position, navigation, and timing (PNT) and data relay services for end-users in cislunar space. PNT solutions will be produced onboard a relay node using radiometric crosslink measurements and distributed to end users. The solutions will achieve absolute states for all users and the relay node using Linked, Autonomous, Interplanetary Satellite Orbit Navigation (LiAISON) The relay node will provide high- and low-data-rate relay services for mission and command and control data, respectively. Accurate timing data is provided to end users over the crosslinks and maintained via a chip-scale atomic clock (CSAC) onboard the relay node.

4:30 PM

AAS-500 : A Study of Orbital Stability and Residual Analysis for Autonomous Lunar Small Satellite Constellations

MOHAMMED IRFAN RASHED (KOREA ADVANCED INSTITUTE OF SCIENCE AND TECHNOLOGY), Hyochoong Bang (Korea Advanced Institute of Science and Technology (KAIST))

The newSpace era is progressive with a creative demonstration of technologies and the methods operating them. The Cislunar competence is evidence that space today needs systems and satellites that are robust, compact, and most of all, enduring the space environment. This paper presents a unique approach to building small satellite constellations over the Moon to support ground operations for missions like Artemis and facilitate enhanced communication relays in the near future. In particular, the orbital stability with a technique integrated with autonomy named 'preferential-EKF' along with its impact on the ground residuals has been demonstrated visually along with significant analysis.

Orbit Determination and Estimation II

Room: Centennial F, Monday, August 12

3:45 PM - 5:00 PM

Session Chair(s): Brandon Jones (The University of Texas at Austin) and Vishal Ray (Kayhan Space)

3:45 PM

AAS-446 : Gauss-Radau: An Investigation Into Varying the Polynomial Degree for Applications in Astrodynamics

David Stanley (The University of Illinois), Robyn Woollands (University of Illinois at Urbana-Champaign)

The 15th-order Gauss-Radau integrator is popular in n-body astrodynamics for its speed and stability. Deviations from the 15th-order scheme are said to increase round-off error and computation time for lower orders, and potential missed close approaches for higher orders. Our study aims to validate these claims across various orders, evaluating computation time, energy conservation, and solution discrepancies. Initial findings reveal trade-offs: Lower-order schemes demand more steps for energy conservation, increasing computational load, while higher-order schemes conserve energy better with fewer steps but require similar computation requirements. Further research will refine error predictions and explore longer integrations in complex scenarios.

4:00 PM

AAS-159 : Navigating Psyche: Launch, Initial Checkout, and Start of Cruise

Nicholas Bradley (NASA / CalTech - JPL), Drew Jones (Jet Propulsion Laboratory, Caltech), Daniel Lubey (Jet Propulsion Laboratory, California Institute of Technology), Dayung Koh (JPL), Courtney Hollenberg (NASA/CalTech Jet Propulsion Laboratory), Jesse Greaves (NASA/CalTech Jet Propulsion Labotatory), Dongusk Han (NASA / Caltech JPL)

The Psyche spacecraft launched on October 13, 2023, en route to the main-belt asteroid (16) Psyche. We present here a navigation-centric summary of the activities from launch through the beginning of cruise thrusting, including assessment of launch injection accuracy, initial acquisition, thruster calibration activities, and the start of long-term cruise thrusting in April 2024. Injection accuracy was excellent, at 1.6-sigma, and valuable navigation data were obtained during the initial checkout activities, allowing the team to characterize the thrusters ahead of long-term operations. Various challenges are also described, along with lessons learned.

4:15 PM

AAS-169 : Automated Filter Tuning For the Fermi Spacecraft

Kerstyn Auman (The Aerospace Corporation), Joshua Lyzhoft (NASA Goddard Space Flight Center), Michael Shoemaker (NASA GSFC), Kenneth Getzandanner (NASA Goddard Space Flight Center)

Utilizing owner/operator ephemeris in collision avoidance algorithms has the potential to improve scalability of comprehensive screenings. Enabling such capability requires constant evaluation and remediation of ephemeris performance via a sliding-window covariance realism assessment and automated covariance tuning. Such a system has been developed for NASA's Fermi Gamma-ray Space Telescope extended mission, where daily covariance quality assurance checks determine whether filter uncertainty elements require tuning via a genetic algorithm. Initial results show that the tuned solution exhibits smaller trajectory prediction state errors and tighter, more realistic position covariances when compared against the initial and outdated, manually tuned filter solution.

4:30 PM

AAS-184 : An Efficient Filter For Measurements Corrupted With Cauchy Noise

James McCabe (NASA Johnson Space Center), **Matthew Gualdoni** (NASA Johnson Space Center)

This paper present a new sequential filter for state estimation using measurements corrupted with Cauchy noise. The new filter retains the familiar structure of the Kalman filter and is computationally efficient. In addition, it does not exhibit computational complexity which grows or varies in time like existing methods. These results are based upon a nearly 50 year old result by Masreliez in which the conditional mean estimator is approximated via linearization of the measurement predictive density. This work derives the new filter, provides discussion regarding practical implementation, and present Monte Carlo analyses to validate and assess the new filter's performance.

4:45 PM

AAS-227 : Covariance Analysis for Gravity Field Reconstruction Around Tumbling Bodies: Applications to Asteroid (99942) Apophis

Anivid Pedros Faura (University of Colorado Boulder), Andrew French (University of Colorado), Julie Bellerose (Jet Propulsion Lab / Caltech), Jay McMahon (CCAR (Colorado Center for Astrodynamics Research))

On April 13, 2029 the asteroid (99942) Apophis will have a close approach to Earth providing a unique opportunity to achieve breakthrough science and to understand the effects of planetary encounters on asteroids. In this work, we identify natural dynamical structures that could be leveraged during the preliminary characterization of Apophis's shape and spin. In the study we discuss different potential spacecraft trajectories that can offer better global coverage as well as the order to which the gravity field could be estimated based on different mission observation times.

Atmospheric Re-entry Guidance and Control
Room: Pine, Tuesday, August 13
8:30 AM - 10:00 AM
Session Chair(s): Tarek Elgohary (University of Central Florida) and Anubhav Gupta (In Orbit Aerospace, Inc. & University of Colorado Boulder)

8:45 AM

AAS-382 : Performance Analysis of Magnetohydrodynamic Drag Modulation for Actively Controlled Aerocapture at Neptune

Danny Nguyen (University of Colorado Boulder), Soumyo Dutta (NASA Langley Research Center), Justin Green (NASA Langley Research Center), Hisham Ali (University of Colorado Boulder)

To maximize the scientific potential of future missions to Neptune, aerocapture has been heavily researched. While aerodynamically-controlled aerocapture has proven enabling, its deep atmospheric pass poses problems with the subsequently necessary thermal protection systems. Magnetohydrodynamically-controlled aerocapture serves as a potential solution to this. Through NASA Langley's high-fidelity Program to Optimize Simulated Trajectories II (POST2), each aerocapture method was simulated and compared for identical missions to Neptune. The results showed that active magnetohydrodynamic control has not only the control authority to successfully capture around Neptune, but also the unique advantage of a shallower atmospheric pass which decreases the maximum heat load.

9:00 AM

AAS-417 : Advancing Complex Differentiation Applications to State transition matrix and Transformed Probability Density in nonlinear dynamics

Koya Yamamoto (Texas A&M University), Patrick Kelly (Texas A&M University), John L. Junkins (Texas A&M University)

This study expands the use of complex differentiation method by applying it in two novel contexts. Firstly, it computes the state transition matrix (STM) for a nonlinear dynamic system with atmospheric drag effects, comparing its accuracy to traditional numerical methods. Secondly, it employs complex step methods to efficiently calculate higher order partial derivatives for computing probability density functions (PDFs) under transformations, especially for multivariable random variables. These applications showcase the versatility and practical utility of the complex differentiation method in applied mathematics and engineering.

9:15 AM

AAS-428 : Advanced Autonomous Numerical Predictor-Corrector Guidance with Final Altitude and Velocity Constraints

Youngro Lee (Iowa State University)

The numerical predictor-corrector guidance with a bank angle parameterization has been employed in various entry examples where only a final range constraint is present. However, a future human Mars landing mission requires an accurate final location and a precise final altitude and velocity at the end of the entry trajectory. This paper proposes to use a quadratic bank parameterization to generate an entry trajectory that satisfies the multi-constraints. A solution space analysis confirms the numerical feasibility of the given entry problem. Monte Carlo simulation results demonstrate the potential applicability of the proposed method for future Human Mars landing missions.

Cislunar Astrodynamics III
Room: Pinon, Tuesday, August 13
8:30 AM - 10:00 AM
Session Chair(s): Damennick Henry (University of Colorado at Boulder) and Mark Muktoyuk (Astroscale US)

8:30 AM

AAS-212 : ASTROMECH: An Augmented Reality Interface for Intuitive Trajectory Design and Tradespace Analysis

David Turner (University of Colorado Boulder), Jay McMahon (CCAR (Colorado Center for Astrodynamics Research))

Even with the aid of state-of-the-art trajectory design tools, cislunar trajectory design tends to require expertise in the highly nonlinear dynamics of the Earth-Moon system. To make this process more intuitive for non-expert operators, this manuscript presents ASTROMECH, an interactive augmented reality trajectory design tool. In this work, we present the capabilities of ASTROMECH that seek to enable fast, intuitive cislunar trajectory design and efficient exploration of the trajectory design tradespace.

8:45 AM

AAS-214 : Attitude Prediction in a Near-Rectilinear Halo Orbit Using a Full Higher-Fidelity Ephemeris Model

Annika Anderson (Embry-Riddle Aeronautical University), Herman Gunter (Embry-Riddle Aeronautical University), David Canales Garcia (Embry-Riddle Aeronautical University), Morad Nazari (Embry-Riddle Aeronautical University)

The ability to predict the attitude of spacecraft in a full ephemeris model for limited orbit types has been demonstrated previously by the authors. However, the Cislunar realm is vast, and future mission plans go beyond geometrically simple orbit cases. The Lunar Gateway is one such mission, which is intended to operate in a near-rectilinear halo orbit (NRHO). In order to ensure the success of Gateway and other missions where coupling between orbital motion and attitude is non-negligible, a comprehensive analysis of those motions on an NRHO is studied in the full ephemeris model for different epochs.

9:00 AM

AAS-218 : A symplectic approach to periodic orbit families in the Hill restricted 4-body problem

Agustin Moreno (University of Heidelberg), Gavin Brown (University of Colorado Boulder), Urs Frauenfelder (Universität Augsburg), Daniel Scheeres (University of Colorado Boulder)

Using the symplectic methods developed by Frauenfelder and Moreno, we carry out numerical studies concerning periodic orbit families for the spatial Hill restricted 4-body problem (HR4BP), which can be seen as time-dependent deformation of the circular restricted three-body problem (CR3BP) in three degrees of freedom. We will then provide insights into the global structure of several families of periodic orbits of current interest.

9:15 AM

AAS-226 : Global Analysis of Optimal Trajectories from Earth-Moon 9:2 Near Rectilinear Halo Orbit to Low-Lunar Orbits

Seur Gi Jo (Embry-Riddle Aeronautical University), Amlan Sinha (Princeton University), Mauro Palomo (ERAU), Jannik Graebner (Princeton University), Annika Anderson (Embry-Riddle Aeronautical University), Justin Schmitt (Embry-Riddle Aeronautical University), David Canales Garcia (Embry-Riddle Aeronautical University), Ryne Beeson (Princeton University)

NASA's Gateway station in the 9:2 near-rectilinear halo orbit (NRHO) will facilitate missions to dock in the cislunar realm before landing on the Lunar surface. Designing a transfer trajectory from NRHO to low-Lunar orbit (LLO) is not a trivial process, with a wide breadth of solutions able to be selected. Optimal trajectory design becomes a global search problem, with countless available solutions that can be generated. Using pydylan for impulsive and low-thrust solutions, this problem is addressed by identifying a range of viable paths, analyzing trends across transfer parameters and conditions, thus providing insights into optimal solutions and architectures.

9:30 AM

AAS-229 : Identifying Structures in Cislunar Space with Topological Data Analysis

Luke Scharck (Auburn University), Davide Guzzetti (Auburn University)

One challenge with describing orbits in cislunar space is the absence of a unified element set. Orbits near Earth benefit from being described by the classical orbital elements to give realization to its geometry. This novel research endeavor applies constructs from topological data analysis to Lyapunov and halo orbital families to characterize each family. The techniques used are the persistence diagram and Wasserstein distance. The persistence diagrams capture the orbital loop of the Lyapunov and halo orbits. The Wasserstein distance reveals increasing orbit sizes amongst the persistence diagrams. Furthermore, the Wasserstein distance depicts the indifference to topological uniqueness between the orbital families with respect to the persistence diagrams.

9:45 AM

AAS-475 : Finite Maneuver Gateway-CubeSat Range and Recontact Analysis Using Stretching Directions

Brennan Blumenthal (The University of Alabama), Rohan Sood (The University of Alabama)

CubeSat deployment from NASA's Gateway is non-trivial due to the complex dynamical environment of the Near Rectilinear Halo Orbit (NRHO) in the lunar vicinity. This investigation identifies differences in potential range and recontact probabilities with Gateway using impulsive, high, and low I_{SP} engine models for the CubeSat deployment ΔV. Results indicate that there can be operationally significant differences in Gateway-CubeSat range and recontact probabilities between impulsive and finite burn maneuvers. Quantifying the associated recontact risks, along with better understanding of the underlying dynamics, will aid with performing safe Gateway-CubeSat deployment operations.

Dynamical Systems Theory Applied to Spaceflight Problems I
Room: Centennial E , Tuesday, August 13
8:30 AM - 10:00 AM
Session Chair(s): Daniel Scheeres (University of Colorado Boulder)

8:30 AM
AAS-120 : Curvature Extrema Along Trajectories in the Circular Restricted Three-Body Problem
Natasha Bosanac (University of Colorado, Boulder)

One approach to summarizing a spacecraft trajectory in a multi-body system involves sampling its periapses and apoapses relative to a reference point. However, in the rotating frame, this trajectory can revolve about one or more primaries, equilibrium points, or other locations. Diverse itineraries create ambiguity in selecting a suitable reference point for a geometrically meaningful apsis. Extrema in the curvature offer an alternative approach for sampling at geometrically meaningful locations and do not require selection of a reference point. This paper examines the characteristics of these extrema in the curvature throughout the phase space in the circular restricted three-body problem.

8:45 AM
AAS-123 : Forecasting the Shape of Phase Space Structures Using an Iso-energetic Symplectic Invariant
Oliver Boodram (University of Colorado Boulder), Daniel Scheeres (University of Colorado Boulder)

Studying the ebb and flow of regions within an orbital environment is important for problems of orbital uncertainty propagation and spacecraft formation flying. This work presents a set of constraints which allow one to analytically forecast aspects of shape related to volumes in space and segments of spacecraft trajectories. Moreover, the constraints give insight into the spacecraft state uncertainty along the local Hamiltonian gradient direction and provide a metric to measure the spacing between objects on a shared nominal trajectory. To recover these constraints, tools from Hamiltonian mechanics and symplectic geometry are leveraged to restrict motion within an iso-energetic manifold.

9:00 AM
AAS-144 : Differential Geometry on Dynamic Surfaces for Astrographic Cartography
Garrick Lau (University of Colorado Boulder), Marcus Holzinger (University of Colorado Boulder)

Terrestrial maps are essential geographic tools to make decisions on best paths and mission designs, and the existence of maps would also greatly benefit decision making in space. In order to make astrographic maps, metric tensors must be determined by distance metrics comprised of mission objectives and coordinates chosen for visualization and planning. This differential geometry of surfaces governed by the dynamics of respective realms, from two body to n-body dynamics, is an important step to creating useful astrographic maps.

9:15 AM

AAS-188 : Optimal Control of Cislunar Trajectories Leveraging Normal Form Methods

Carson Hunsberger (The Pennsylvania State University), David Schwab (The Pennsylvania State University), Roshan Thomas Eapen (The Pennsylvania State University), Puneet Singla (The Pennsylvania State University)

The normal form coordinates of the circular restricted three-body problem provide an approximate semianalytic solution to the dynamics near the libration points. The major benefit of these coordinates are that they provide features which may be exploited by other algorithms. This work explored the use of these features--the normal form coordinates--in defining optimal control problems, including the transfer and station-keeping of a Lissajous quasiperiodic trajectory.

9:30 AM

AAS-221 : On Robust Low Thrust Trajectories and Invariant Manifolds (Part II)

Amlan Sinha (Princeton University), Ryne Beeson (Princeton University)

As low-thrust missions become more common, particularly in the cislunar realm, it is increasingly important to design low-thrust trajectories that are made robust against unforeseen thruster outages, known as missed thrust events. By using a set of distance metrics on Poincare sections, this study sheds light on how the robust trajectories differ from their non-robust counterparts in terms of the dependence on the underlying dynamical structures in multibody gravitational environments with an aim toward improving robust trajectory design. We examine how the dependence changes with the parameters characterizing missed thrust events, notably the initiation time and outage duration.

Space Domain Awareness (SDA) and Space Surveillance II
Room: Centennial F, Tuesday, August 13
8:30 AM - 10:00 AM
Session Chair(s): Casey Heidrich (University of Colorado Boulder) and Smriti Nandan Paul (Missouri University of Science and Technology)

8:30 AM
AAS-111 : Averaged Spin State Catalog for Uncontrolled Space Objects
Conor Benson (The Aerospace Corporation)

The attitude dynamics of high-altitude objects are primarily affected by solar radiation torques. We develop a spin-averaged, “shape model free” spin state catalog framework for uncontrolled space objects and apply it to real observations of defunct GEO objects. Semi-analytical spin-averaged equations of motion allow for fast, accurate attitude propagation months or years into the future. Averaging lets us boil all object mass, shape, and optical properties down to constant torque curves that can be readily approximated with Fourier series. Using synodic spin rate measurements, we estimate an object’s sidereal spin rate, inertial spin axis, and solar + gravity gradient torque coefficients in a batch filter.

8:45 AM
AAS-315 : Parameters Estimation in Source-Sink Space Population Evolutionary Models
Erin Ashley (Iowa State University), Simone Servadio (Iowa State University), Carla Simon (Iowa State University), Giovanni Lavezzi (Massachusetts Institute of Technology)

Expansion and refinement of an existing Monte-Carlo method for simulating the Low Earth Orbit (LEO) environment is developed in this work. The MIT Orbital Capacity Analysis Tool (MOCAT) simulates the Low Earth Orbit (LEO) environment. This work expands on the MOCAT analysis by introducing a Kalman filter step to the simulation process for greater accuracy in estimations of the LEO environment over time. A performance index for different distribution fitting parameters based on previous MOCAT simulation results is developed in this work.

9:00 AM
AAS-327 : Analysis of Covariance-based Track Association Methods in Cislunar Space
Woosang Park (Texas A&M University), Kyle T. Alfriend (Texas A&M University)

The purpose of this paper is to investigate the applicability and efficacy of the covariance-based track association (CBTA) method for cislunar space objects. We analyze the Mahalanobis distance with time for Lyapunov, distant retrograde orbit, and halo orbit in the Circular Restricted Three-Body Problem (CR3BP). According to Liouville's theorem in Hamiltonian mechanics; if the uncertainty is propagated with a full, nonlinear dynamics, the Mahalanobis distance remains constant. Therefore, the Gaussian Mixture Model (GMM) and Monte Carlo simulation are used to propagate the covariance, hoping that we can delay the degradation of the Mahalanobis distance under the highly nonlinear CR3BP dynamic model.

9:15 AM

AAS-427 : Control of Satellite Formations Near Earth-Moon Lagrange Points for Interferometric Characterization of Cislunar Objects

Erin Fowler (University of Maryland College Park), Derek Paley (University of Maryland College Park)

This manuscript describes a formation selection and control scheme, based on Bravais lattice configurations, for interferometric imaging of other spacecraft in the cislunar regime by a spacecraft formation near a collinear Earth-Moon Lagrange point. This research will describe the value of space-based interferometry for the cislunar space domain awareness mission using metrics for interferometric imaging and object tracking and will quantify the control cost for the proposed formation control scheme.

9:30 AM

AAS-462 : Dynamic Triangulation For Cislunar Initial Orbit Determination

Liam Smego (Georgia Institute of Technology), John Christian (Georgia Institute of Technology)

Currently there is a demand for cislunar IOD algorithms, because the non-Keplerian dynamics of the region reduce the performance of traditional, two-body methods. We propose an approach based on dynamic triangulation, an algorithm that estimates a vehicle's full state with sequential LOS measurements. In this approach, the RSO's motion is approximated as rectilinear over a relatively short period of its orbit, which allows us to use dynamic triangulation to generate an initial guess of its state. This guess is then refined by minimizing the measurement residuals using a nonlinear least squares solver and the full dynamic model.

Cislunar Astrodynamics IV
Room: Pinon, Tuesday, August 13
10:30 AM - 12:30 PM
Session Chair(s): Diane Davis (NASA Johnson Space Center) and Anthony Genova (NASA)

10:30 AM

AAS-249 : Using Fast Lyapunov Indicators with 4D Poincare Maps to Identify Transforming Quasi-Periodic Orbits

Tyler Kapolka (USSF), Robert Bettinger (Air Force Institute of Technology, Department of Aeronautics & Astronautics), Kerry Hicks (Air Force Institute of Technology)

Fast Lyapunov Indicator (FLI) maps and Poincarè maps are two common methods for analyzing complex dynamical systems. These maps are complicated to assess for the spatial circular restricted three-body problem due to the high number of dimensions. This paper proposes a method of using FLI in conjunction with 4D Poincarè maps to more easily search for spatial periodic and quasi-periodic trajectories. The use of FLI to filter trajectories displayed in a 4D Poincarè map allows for the benefits of the Poincarè map to be realized while taking advantage of the ability of FLI to distinguish between stable and unstable trajectories.

10:45 AM

AAS-258 : Long Duration Explicit Symplectic Approximations And Uncertainty Propagation For Cislunar Regimes

Anabel Soria Carro (The University of Texas Austin), Maruthi R. Akella (The University of Texas at Austin)

Hamiltonian mechanics offers analytical and geometric insights unattainable by other alternative methods. These insights are valuable for developing perturbation theory methods in astrodynamics. In numerous instances documented in the literature, separable Hamiltonians can use explicit symplectic integrators, such as the Störmer Verlet method, to preserve phase space and the underlying constants of motion during numerical propagation. This paper reveals that explicit symplectic integrators can be employed, even in the non-separable Hamiltonian systems of the Circular and Elliptic Restricted Three-Body dynamics. Furthermore, numerical experiments confirm their superiority in stability and speed for long-term propagation, maintaining integrals compared to traditional non-symplectic methods.

11:00 AM

AAS-293 : Time-Delayed Dynamic Mode Decomposition for families of periodic trajectories in Cislunar space

Sriram Narayanan (The Ohio State University), Mohamed Naveed Gul Mohamed (Texas A and M University), Indranil Nayak (Ohio State University), Suman Chakravorty (Texas A&M University), Mrinal Kumar (The Ohio State University)

In recent years, there has been renewed interest in lunar exploration, both manned and unmanned, driven by the development of the Lunar Gateway and Artemis missions. This interest motivates the need for accurate initial orbit determination (IOD) and orbit prediction(OP) in this regime facing formidable challenges such as severe nonlinearity, sensitivity to initial conditions, enormous state-space volume, and sparse, faint, and unreliable measurements. This work discusses the capability of Koopam operator-based approximations for OP in such scenarios. Theoretical reasoning for the use of a linear time-invariant system is provided and validated via experimental analysis.

11:15 AM
AAS-298 : Regularization of the Circular Restricted Three-body Problem for Trajectory Optimization
Kenshiro Oguri (Purdue University)

Any objects in space may encounter singularity due to the inverse-square law of the gravitational force, causing numerical issues in solving differential equations for orbit propagation. The presence of singularity becomes particularly detrimental when analyzing, predicting, and/or designing trajectories in multi-body dynamics. This paper first leverages the theory of regularization to express the circular restricted three-body problem without singularity. Then, we combine it with Pontryagin's principle to formulate a singularity-free low-thrust trajectory optimization framework in multi-body dynamics. This paper demonstrates the effectiveness of the developed framework in cislunar space, using transfers around Earth-Moon Lagrange points and across cislunar space.

11:30 AM
AAS-305 : Cislunar Trajectory Design for Constellations Leveraging Sidereal-Synodic Resonant Behavior
Maaninee Gupta (Purdue University), Kathleen C. Howell (Purdue University)

To establish a comprehensive SSA architecture in cislunar space, space-based sensors that can traverse the expansive volume are currently an option being evaluated. With the availability of unique vantage points across the domain of cislunar space via sidereal resonant orbits, orbits that are additionally commensurate with the lunar synodic period provide options for feasible visibility conditions that persist over time. Metrics for evaluating the visibility of various targets as viewed by space-based observers are leveraged to assess and design observer trajectories.

11:45 AM
AAS-313 : Dynamics Leveraged in Long-Term Stationkeeping Strategies for Multi-Body Orbits
Dale Williams (Purdue University), Kathleen C. Howell (Purdue University), Diane Davis (NASA Johnson Space Center)

Increased interest in the development of cislunar space requires greater intuition for the operation of spacecraft in multi-body orbits. Many such orbits are linearly unstable, and an orbit maintenance strategy is required to secure a spacecraft near some desired reference motion. The development of effective stationkeeping ap[1]proaches is facilitated by improved understanding of the variational dynamics near a periodic orbit. In this investigation, Floquet Theory is applied to explore the under[1]lying dynamics leveraged and controlled by several orbit maintenance approaches. The dynamical requirements for long-term stationkeeping effectiveness is also ex[1]amined.

12:00 PM

AAS-319 : Autonomous Navigation Strategy for Low-Energy Transfers with Limited Ground-Based Updates

Yuri Shimane (Georgia Institute of Technology), Sebastien Henry (Georgia Institute of Technology), John Christian (Georgia Institute of Technology), Koki Ho (Georgia Institute of Technology)

With increasing traffic in cislunar space, autonomous navigation for translunar trajectories is increasingly important. Low-energy transfers (LET), with apogees well beyond the Moon's orbit and times of flight extending over multiple months, will greatly benefit from navigation with minimal reliance on ground-based navigation updates. In this work, we first study the extent to which optical navigation techniques, namely triangulation-based and horizon-based algorithms, may be used for onboard navigation without any ground-based updates. This is followed by formulating the measurement scheduling problem, where we solve for the optimal schedule to provide a limited number of ground-based measurements that minimize the onboard navigation uncertainty along the LET.

Orbit Determination and Estimation III
Room: Pine, Tuesday, August 13
10:30 AM - 12:30 PM
Session Chair(s): Nicholas Bradley (NASA / CalTech - JPL) and Siamak Hesar (Kayhan Space)

10:30 AM
AAS-231 : Orbit Determination Demonstration using Onboard One-way Radiometrics from the Iris Radio on the CAPSTONE Mission
Todd Ely (California Institute of Technology), Zaid Towfic (Jet Propulsion Laboratory, California Institute of Technology), John Baker (Jet Propulsion Lab), Dana Sorensen (Space Dynamics Laboratory), Anthony Zara, Connor Ott, Alec Forsman (Advanced Space, LLC)

One-way radiometric tracking using the Iris radio paired with a Chip Scale Atomic Clock (CSAC) has sufficient accuracy to enable autonomous radio navigation for missions with modest requirements. Iris/CSAC is on NASA's CAPSTONE mission to demonstrate one-way tracking and use it to determine its near rectilinear halo orbit. Ground test results have shown Iris/CSAC can form range rate and range with ~11 mm/s at 60-seconds and ~2.2 m precision, respectively. This work will compare the space-based data with these results, as well as assess CAPSTONE's orbit solution accuracy from the one-way data and compare it to ground two-way tracking solutions.

10:45 AM
AAS-244 : L2-Squared Divergence Search Algorithm for Initial Orbit Determination using Radio Frequency Measurements
Evan Hefflin (Texas A&M University), Kyle DeMars (Texas A&M University)

Radio frequency measurements have been utilized for performing probabilistic initial orbit determination of nearby spacecraft. Using time difference of arrival and frequency of arrival measurements, an admissible region of the state of a spacecraft can be formed and autonomously searched by narrow field of view sensors on the Earth. This paper investigates a search algorithm that utilizes the L2-squared divergence to determine the optimal sensor boresight that captures the most information within each detection by computing the divergence between the prior admissible region and a posterior formed by assumed target detections.

11:00 AM
AAS-246 : Spacecraft Maneuver Detection and Tracking using the Hybrid Bernoulli Filter
Evan Hefflin (Texas A&M University), Kyle DeMars (Texas A&M University)

As more active satellites orbit the Earth, spacecraft maneuver detection and tracking techniques are necessary for future space domain awareness architectures. Spacecraft maneuver estimation is generally difficult due to the stochastic switching of actuated dynamics, and further developments are critical to maintain tracking through these scenarios. This paper discusses the hybrid Bernoulli filter where hybrid Bernoulli densities are manipulated to create and propagate multiple hypotheses of motion to capture these maneuvering dynamics. The performance of the filter is evaluated for detecting small maneuvers and tracking targets in low Earth and geosynchronous orbits in the presence of perturbations.

11:15 AM

AAS-282 : IM-1 Orbit Determination: A Comparison of Mission Deliveries vs Post-Flight Trajectory Reconstruction

Donald Kuettel (Intuitive Machines), Jason Leonard (KinetX), Jeroen Geeraert (KinetX Inc.), Michael Salinas (KinetX Aerospace), Shen Ge (Intuitive Machines), Samuel Welsh (Intuitive Machines), Shaun Stewart (Intuitive Machines), Peter Antreasian (KinetX Aerospace)

Intuitive Machines' (IM) inaugural mission, IM-1, was launched on 2/15/2024 at 06:05:00 UTC on a SpaceX Falcon 9 from Kennedy Space Center. The IM-1 spacecraft, a Nova-C class lander named Odysseus, landed near the Malapert A crater on 2/22/2024 at 23:23:00 UTC. Odysseus used radiometric tracking data from IM's Lunar Telemetry Network, supplemented by short-duration passes from the Deep Space Network, to successfully navigate into lunar orbit and then descend to the surface of the Moon. This paper summarizes the operation experiences, navigation results, and lessons learned by the IM and KinetX Ground Navigation teams and compares the ``as flown'' trajectory to the post-mission reconstructed trajectory.

11:30 AM

AAS-286 : Nonlinear State And Mass Property Estimation On TSE(3) During Undocking Maneuvers In The Cislunar Region

Herman Gunter (Embry-Riddle Aeronautical University), Morad Nazari (Embry-Riddle Aeronautical University), Marco Fagetti (Embry-Riddle Aeronautical University), Matthew Wittal (National Aeronautics and Space Administration), Jeffrey Smith (Gateway Logistics Element, NASA Kennedy Space Center)

Mass property estimation is a nontrivial problem within astrodynamics that can lend many advantages to astrologically located missions allowing for reductions in crew time spent upon tasks that might alter mass properties. The estimation of such properties is accomplished via a dual unscented Kalman filter developed considering dynamics on the special Euclidean group SE(3) and its tangent bundle TSE(3). Further improvements upon this algorithm are demonstrated to allow implementation outside of classical Keplerian orbits through use of the circular restricted full three-body problem and incorporation with higher-order gravitational terms that introduce nonlinearities with respect to the mass properties.

11:45 AM

AAS-307 : Nonlinear Estimation with Intrusive Polynomial Chaos and Multi Fidelity Propagation

Zee Toler (The University of Texas at Austin), Brandon Jones (The University of Texas at Austin)

Linear filtering methods cannot always provide consistent estimates for systems with nonlinear dynamics and measurement models. This has led to application of nonlinear uncertainty quantification (UQ) and filtering to current orbit determination challenges. Polynomial Chaos Expansions (PCEs) are capable of modeling non-Gaussian uncertainty under sparse measurements and long propagation times. Multi fidelity methods, where a low number of high-fidelity samples are used to correct a lower fidelity solution, have also seen use in UQ to balance efficiency and accuracy. This work improves upon the authors' nonlinear intrusive PCE-based filter with a multi-fidelity time update applied to the perturbed orbits problem.

12:00 PM

AAS-331 : Ephemeris Reconstruction for Comet 67P/Churyumov-Gerasimenko during Rosetta's Proximity Phase from Radiometric Data Analysis

Riccardo Lasagni Manghi (Alma Mater Studiorum - Università di Bologna), Marco Zannoni (University of Bologna), Paolo Tortora (Alma Mater Studiorum - Università di Bologna), Frank Budnik (European Space Agency), Bernard Godard (European Space Agency)

This study provides an accurate ephemeris reconstruction for comet 67P/Churyumov-Gerasimenko between July 2014 and October 2016, during Rosetta's proximity phase, by reanalyzing Earth-based radiometric and astrometric measurements. Given the comet-to-spacecraft relative trajectory provided by the navigation team, Rosetta measurements were used to estimate the comet state and the non-gravitational accelerations induced by the outgassing of sub-surface volatiles, for which several models were tested and compared. The reference solution, which exploits empirical models, provides an agnostic estimation of the comet's non-gravitational motion, which could be used as a constraint for future investigations involving high-fidelity thermophysical models of the comet's surface.

Spacecraft Guidance, Navigation and Control (GNC) III
Room: Centennial E , Tuesday, August 13
10:30 AM - 12:30 PM
Session Chair(s): Greg Dukeman (NASA) and Jay McMahon (CCAR (Colorado Center for Astrodynamics Research))

10:30 AM
AAS-245 : Extended Target Tracking Using LIDAR for Spacecraft Relative Navigation
Alexander Perruci (Iowa State University), David Lee (Iowa State University)

Increasing interest in space debris removal and on-orbit servicing have motivated research in autonomous relative navigation algorithms using Light Detection And Ranging (LIDAR) sensors. We implement an Extended Target Tracking (ETT) technique to estimate the relative position, attitude, and kinematics of a noncooperative and unknown target. A weighted sum of spherical harmonics basis functions models the target surface. As LIDAR point clouds are collected, the Multiplicative Extended Kalman Filter estimates the weights simultaneously with the 6-degree-of-freedom relative states. Results of simulated rendezvous with a CubeSat show successful relative navigation without prior information about the target shape or states.

10:45 AM
AAS-253 : Revisiting Optimal Guidance Solution for Vertical Landing and Take-Off
Bharat Mahajan (Odyssey Space Research LLC)

The vertical landing and take-off are crucial phases of a space vehicle's powered descent and ascent trajectories, during which the vehicle's motion is confined to a single (vertical) axis. It is well-known that the minimum-propellant guidance solution for vertical landing and take-off in a vacuum, consists of the coast and full-thrust arcs only and no singular arc exists in this problem, however, an exact analytical solution for this problem is not found in the literature. In the present work, an exact analytical solution for the optimal vertical landing and take-off guidance problem is derived that provides the closed-loop analytical expression for the switching function between the coast and full-thrust phases.

11:00 AM
AAS-271 : Spacecraft State Estimation on TSE(3) in the Presence of Slosh Modeled as a Moving, Pulsating Ball
Marco Fagetti (Embry-Riddle Aeronautical University), Herman Gunter (Embry-Riddle Aeronautical University), Morad Nazari (Embry-Riddle Aeronautical University), Matthew Wittal (National Aeronautics and Space Administration), Michael Elmore (a.i. solutions), Jeffrey Smith (Gateway Logistics Element, NASA Kennedy Space Center)

This paper revisits a state estimation scheme utilized for the motion of a rigid body in the presence of disturbances caused by a sloshing liquid on the vehicle. The estimation scheme is based on an unscented Kalman filter formulated on the
special Euclidean group SE(3) and its tangent bundle TSE(3). The sloshing dynamics of the liquid are represented by a moving, pulsating ball model, providing a higher fidelity representation of sloshing behavior in microgravity. In the final manuscript, the state estimation of the liquid propellant will be validated on a generic model of a Gateway logistics vehicle.

11:15 AM
AAS-297 : Measurement-Informed Constrained Stochastic Reachability via Convex Optimization
William Fife (Texas A&M University), Kyle DeMars (Texas A&M University)

A method is presented to solve a constrained stochastic reachability problem while considering measurement information. The objective is to determine the largest area of feasible initial states and associated open loop control such that any state within this area will be driven to the target set while abiding state and control constraints. The problem is formulated as a chance constrained convex optimization problem, allowing the algorithm to be executed with efficiency and reliability. Inclusion of the measurement information results in overall less conservative solutions than the measurement-uninformed counterparts. The method is evaluated via Monte Carlo analysis on two dynamical system examples.

11:30 AM
AAS-328 : A Multi-Order Shooting Scheme Applied to Low-Thrust Trajectory Optimization
Sharad Sharan (Pennsylvania State University), Roshan Thomas Eapen (The Pennsylvania State University), Puneet Singla (The Pennsylvania State University), Robert Melton (Pennsylvania State University)

This paper proposes a novel multi-order shooting scheme (MOSS) that serves to expand the convergence regions of indirect optimization methods, thereby alleviating the burden of requiring good initial guesses. The necessary higher-order sensitivities are computed using a derivative-free approach that reduces the computational costs associated with traditional sensitivity computation methods. In this paper, MOSS is successfully applied to a low-thrust minimum fuel problem. Significant improvement in convergence is observed when compared against a traditional shooting method. MOSS is also used to identify heteroclinic connections between periodic orbits as solutions to the minimum-fuel problem, without the need for Poincare maps.

11:45 AM
AAS-356 : Station Keeping of Areostationary Mars Orbit Satellites Using Linear Time-Varying Model Predictive Control
Nathan Gall (University of Minnesota), Robert Halverson (University of Minnesota - Twin Cities), Ryan Caverly (University of Minnesota)

Areostationary Mars Orbit (AMO) satellites are of key interest to future crewed and uncrewed missions to Mars. Due to the large gravitational perturbations experienced by AMO satellites, efficient station keeping policies are required. Model Predictive Control (MPC) has been shown to be effective for fuel efficient AMO station keeping, but requires a computationally expensive nonlinear prediction model for the best results. In this paper we reformulate a linear-quadratic MPC policy to accomodate a linear-time-varying prediction model. When compared to previous linear policies in numerical simulations, this new policy is shown to better capture the effects of perturbations leading to a more efficient controller.

12:00 PM

AAS-371 : Probabilistic Regression for Autonomous Terrain Relative Navigation via Multi-Modal Feature Learning

Ickbum Kim (Rensselaer Polytechnic Institute), Sandeep Singh (Rensselaer Polytechnic Institute)

The extension of human spaceflight across an ever-expanding domain, in conjunction with intricate mission architectures demands a paradigm shift in autonomous navigation algorithms. Deep learning architectures have previously been explored to perform low-dimensional localization with limited success. In the current work, a novel formulation is proposed to train CNN-based deep learning (DL) models in a multi-layer cascading architecture and utilize the resulting classification probabilities as regression weights to estimate the two-dimensional position of the lander spacecraft. The approach leverages image intensity as well as embedded depth information to effectively determine the location of a spacecraft relative to the observed terrain.

12:15 PM

AAS-374 : Enhanced simultaneous range measurement and clock synchronization with the advanced deep space missions – theories and experiments

Junichiro Kawaguchi (School of Engineering, College of Engineering and Computer Cybernetics, Australian National University), Shingo Nishimoto (Australian National University (anu)), Saki Komachi (Tohoku University), Hayato Kokubo (Tohoku University)

The Asynchronous One-Way Range (AOWR) scheme was devised by the authors as an alternative method for the radio transponders in deep space flight. The current AOWR method is based on pseudo-range, and the accuracy/stability is limited due to fluctuations. The paper proposes a new estimator using the carrier-phase data exchanged, which shows minimal fluctuation, and the results are presented. The paper presents applications of the AOWR scheme to an innovative navigation system around the moon and small bodies. The system involves navigating an ascent probe to the mother spacecraft in orbit for transferring samples .

Trajectory, Mission, and Maneuver Design/Optimization V
Room: Centennial F, Tuesday, August 13
10:30 AM - 12:30 PM
Session Chair(s): Robert Melton (Pennsylvania State University) and David Spencer (The Aerospace Corporation)

10:30 AM

AAS-304 : Development of Global Topology Algorithms Applied to a Lyapunov-Based Guidance Law for Low-Thrust Elliptic Keplerian Transfers

Benjamin Benjadol (Princeton University), **Ryne Beeson** (Princeton University)

Solution of multiple revolution low-thrust transfers for the two-body problem often rely on averaging methods, shape-based or series expansion approximations, weighted guidance laws, or candidate Lyapunov functions (e.g, Q-law). In this paper, we aim to further a Lyapunov-based theory with locally asymptotically stable convergence, but which currently lacks guidance on the global aspects of the theory and algorithm choices. Additionally, we take inspiration from Q-law to further improve the solved efficiency of our algorithm and provide comparisons to Q-law on a set of benchmark problems.

10:45 AM

AAS-322 : Co-Optimization of Spacecraft and Low-Thrust Trajectory with Direct Methods

Keziban Saloglu (Auburn University), Ehsan Taheri (Auburn University)

Solar-powered electric propulsion systems can operate in multiple modes, which are coupled to the power generation by solar arrays. The solar power is a function of the solar array size and heliocentric distance, which also depends on the trajectory. In this work, we co-optimize the spacecraft's solar array size, thruster modes, and trajectory using a direct method. The increased fidelity allows for maximizing the net delivered mass. The co-optimization problem is formulated as an optimal control problem using a direct method, and the CasADi tool is used to implement and solve the corresponding problems. The utility of the method is shown by solving the Earth to Comet 67P interplanetary rendezvous problem.

11:00 AM

AAS-335 : Robust Trajectory Optimization Techniques Using a Sweeping Gradient Method and Linear Covariance Analysis

Benjamin Margolis (NASA Ames Research Center), **David Woffinden** (NASA Johnson Space Center)

We present robust trajectory optimization techniques using a sweeping gradient method for ordinary differential equations with events (SGM) and linear covariance analysis (LinCov). SGM is a method for computing the gradient of trajectory analyses defined by performance indices over initial value problems with events with respect to static parameters. LinCov is an analytic technique for predicting stochastic behavior of dynamical systems. By combining SGM and LinCov, it is possible use efficient, off-the-shelf, gradient-based optimizers to solve robust optimal trajectory design problems. We describe the individual methods and some details on how they can be combined. Then we apply the combined techniques to a variety of orbital trajectory design problems.

11:15 AM

AAS-254 : A Human-Centric Comparative Analysis of Trajectory Design Methods for Multi-Body Dynamics

Edison Martinez-Samaniego (Embry Riddle Aeronautical University), Michelle Aros (Embry Riddle Aeronautical University), Laith Bader (Auburn University), Justin Schmitt (Embry-Riddle Aeronautical University), Lily Auerback (University of Maryland, Baltimore County), Joseph Anderson (Embry Riddle Aeronautical University), Karis Cooks (Embry Riddle Aeronautical University), David Canales Garcia (Embry-Riddle Aeronautical University), Barbara Chaparro (Embry Riddle Aeronautical University), Davide Guzzetti (Auburn University)

Trajectory design in the CR3BP is a complex but crucial process for understanding systems in the realm of multiple celestial bodies. By focusing on a human factor's perspective, this research aims to compare AR, VR, STK, and GMAT for solving trajectories. While preliminary work indicates AR's potential in enhancing user interface intuitiveness and visualization when compared to STK, for successful mission design, this study focuses on the usability, visualization, and collaboration aspects of all tools, providing insights into each method's effectiveness and user-friendliness. Overall, this research contributes to advancing mission planning efficiency and human-centered design principles in space trajectory design.

11:30 AM

AAS-302 : Comparison of control regularization techniques for minimum-fuel low-thrust trajectory design using indirect methods

Ehsan Taheri (Auburn University), Saeid Tafazzol (Auburn University), Nan Li (Auburn University)

It is known that minimum-fuel low-thrust trajectory optimization problems may have a finite, but unknown number of switches in the thrust profile (a.k.a., bang-off-bang) that pose challenges to the efficiency of numerical methods that are typically used for solving the Hamiltonian two-point boundary-value problems (HTPBVPs). Our objective is to compare the impact of the hyperbolic-tangent-based smoothing to a recently introduced L2-norm-based smoothing on the convergence performance of numerical methods. Both of these smoothing methods belong to the class of control regularization. Additionally, we examine the application of each method in scenarios where the State Transition Matrix (STM) is employed. The capability of each method for solving minimum-fuel low-thrust trajectory optimization problems are investigated.

11:45 AM

AAS-348 : A Mission Planning Technique for Low-Thrust Synergetic Gravity-Assist Missions

Ghanghoon Paik (Pennsylvania State University), Robert Melton (Pennsylvania State University)

Multiple gravity assists are an important technique for science missions with associated interplanetary trajectories. A low-thrust synergetic maneuver is a unique technique that is applied in this research. This technique performs thrusted maneuvers while inside a planet's sphere of influence. In order to apply such a technique, Tisserand's graphs and porkchop plots are analyzed to find proper sequences and phasing results. A heuristic optimization method is used to find optimal thrust characteristics. The method is designed to quickly run on a desktop PC (run time of minutes to hours).

12:00 PM

AAS-376 : Stochastic Advance ΔV99 Evolutionary Optimization - An Application to Europa Clipper

Vishala Arya (Jet Propulsion Laboratory), Etienne Pellegrini (Jet Propulsion Laboratory), Stefano Campagnola (Jet Propulsion Laboratory), Andrew French (University of Colorado)

Europa Clipper will investigate the habitability of Europa with 50+ flybys, each submitted to stringent science constraints making it an operationally challenging mission. The nominal trajectory design corrects small maneuver execution and state knowledge errors, but does not accommodate missed maneuvers or other large errors. This work will automatically produce an alternative segment design when encountered by a large error, that connects back to the original tour after a set of N flybys. The main goal is not just to automate this alternate segment design with deterministic maneuvers but to also minimize the stochastic fuel consumption while respecting constraints like the probability of impact with any body in the Jovian system.

Asteroid and Interplanetary Mission Design I
Room: Pinon, Tuesday, August 13
2:00 PM - 3:15 PM
Session Chair(s): Jeroen Geeraert (KinetX Inc.)

2:00 PM
AAS-301 : High Frontier - A Private Asteroid Excavation Mission: Design and Development Analysis
Dianna Velez (Karman+), Kalle Anderson (Karman+), Dale Howell (Karman+), Lisa Whittle (Karman+), Fiona Boyce (Karman+), Lauri Siltala (Karman+), Daynan Crull (Karman+), Simon Hallam (Karman+), Teun van den Dries (Karman+)

Karman+ is a commercial venture developing a mission, High Frontier, to a near-Earth asteroid for kilogram scale sample excavation. Our first mission is taking on a number of mission design and navigation challenges. Solar electric propulsion will perform the Earth escape spiral and interplanetary cruise. To reduce ground resource dependencies during cruise, optical navigation will be processed by an autonomous navigation system. Descent to the asteroid will use simultaneous localization and mapping to maneuver "touch-and-go" use of excavation equipment. This paper will go over the design, tools, and techniques, under development and analysis in preparation for a preliminary design review.

2:15 PM
AAS-334 : Trajectory Design and Uncertainty Analysis for Impactor Deployment in a Binary Asteroid System
Noble Hatten (Johns Hopkins University Applied Physics Laboratory), Ronald Ballouz (Johns Hopkins University Applied Physics Laboratory), Daniella DellaGiustina (University of Arizona), Kevin Walsh (Southwest Research Institute), Veronica Bray (Lunar and Planetary Laboratory)

The deployment of a seismometer on the surface of the primary or secondary of a binary asteroid system would provide unique and novel insight into the interior of asteroids. In this work, we study the trajectory design required to deploy an impactor from a carrier to the surface of the primary of a binary system with impact characteristics that meet seismometer delivery requirements (e.g., the seismometer must bury into the surface). Given the significant uncertainties surrounding impactor deployment (e.g., carrier pre-deployment state, deployment impulse, asteroid characteristics), we also examine the robustness of deployment scenarios via Monte Carlo simulations.

2:30 PM
AAS-340 : IM-1 Pre-Mission Landing Site Evaluation
Jamie Murray (Intuitive Machines), Shen Ge (Intuitive Machines)

Landing site selection and evaluation is critical for any lunar lander mission. Choosing an appropriate location within a certain error ellipse that must satisfy both vehicle and mission constraints is challenging. The vehicle must land in an area with acceptable slope and hazard characteristics. Mission requirements are dictated by a minimum surface duration to satisfy payload operations which account for visibility with Earth to maintain communications and visibility to the sun for power generation. Intuitive Machines (IM) with the support of Arizona State University (ASU) developed a process and toolset which enabled us to choose a successful intended landing site for our first mission. This toolset has subsequently been used

2:45 PM

AAS-344 : Interplanetary Sensitivity Studies of The Emirates Mission To The Asteroid Belt (EMA)

Fatema Alhameli (UAE Space Agency), Jeff Parker (Advanced Space, LLC), Jeremy Knittel (Laboratory for Atmospheric and Space Physics (LASP))

Scheduled for launch in 2028, the Emirates Mission to the Asteroid Belt (EMA) spacecraft, known as MBR Explorer, will visit six asteroids in the asteroid belt and rendezvous with a seventh, *269 Justitia* by 2034. As a solar electric propulsion (SEP) mission, there are many models and assumptions that go into designing this interplanetary trajectory. Much recent work has gone into understanding the sensitivity of the trajectory and the overall mission objectives with respect to these inputs. This paper will overview the most recent updates to the EMA mission trajectory as well as documenting these sensitivity analyses.

Dynamical Systems Theory Applied to Spaceflight Problems II
Room: Centennial E , Tuesday, August 13
2:00 PM - 3:15 PM
Session Chair(s): Natasha Bosanac (University of Colorado, Boulder)

2:00 PM

AAS-230 : Semi-Analytical F and G Series Solutions for the Circular Restricted Three-Body Problem

Ryan Menges (University of Colorado Boulder), Daniel Scheeres (University of Colorado Boulder)

The use of non-recursive Taylor series expansions, derived with higher-order time derivatives of the equations of motion, is explored in the Circular Restricted Three-Body Problem (CR3BP). Implementing this semi-analytical F and G series approach allows for the propagation and estimation of a spacecraft's position and velocity in cislunar space, linked directly to the progression of time. These solutions are validated by comparisons to numerically integrated periodic orbits and a truncation error analysis on higher-order terms of the series. Applications discussed include a recursive approach to extend accuracy, propagation of the state transition matrix derived analytically, and orbital targeting.2:15 PM

AAS-239 : Analysis of Dynamical Structures in a Three-Dimensional Volume-Preserving Map

Naoki Hiraiwa (Kyushu University), Damennick Henry (University of Colorado at Boulder), Mai Bando (Kyushu University), Daniel Scheeres (University of Colorado Boulder)

Geometrical trajectory design methods often utilize Poincare maps to extract characteristics of the dynamics in the planar problem. However, the extension of these methods to the spatial problem is challenging due to its high dimensionality. To address this issue, this paper aims to develop computational tools for analyzing a three-dimensional volume- and orientation-preserving map called the ABC map and identify dynamical structures called lobes in this dynamics. The ABC map in three dimensions works as an intermediate case between the Poincare map in the planar and spatial problem. The obtained results contribute to analyzing dynamical structures in higher-dimensional systems.

2:30 PM

AAS-248 : Dynamics of Spacecraft with General Translating Appendages Using the Backsubstitution Method

João Vaz Carneiro (University of Colorado Boulder), **Peter Johnson** (University of Colorado Boulder), Hanspeter Schaub (University of Colorado)

Spacecraft mission requirements have increasingly required that spacecraft physically interact with other bodies, whether for servicing operations or landing on asteroids and other planets. The spacecraft interaction is done through a translating arm, usually with some damping mechanism for either application. This is particularly evident in the landing missions since the telescopic arm contacts the asteroid to collect samples while dampening the landing and pushing the spacecraft back into orbit. These important use cases motivate the need to understand and analyze spacecraft behavior with translating appendages. This work presents an analytic derivation of the equations of motion of spacecraft with these appendages using a general, modular approach.

2:45 PM

AAS-251 : Nonlinear Observability of Cislunar Relative Navigation Using Automatic Differentiation

Matthew Givens (Advanced Space), Benjamin Tatman (Advanced Space), Anthony Zara

Building on work in nonlinear observability theory and computational methods, we showcase some preliminary results from a new observability analysis tool that leverages automatic differentiation based on Google's open source JAX library. The tool can operate on any nonlinear autonomous dynamics model and any nonlinear measurement model to compute an observability matrix given some state configuration, from which the rank test and a state-wise observability metric can be derived. We demonstrate the tool's use in a cislunar scenario with relative range and range rate measurements and propose new visualization concepts for understanding the geometry of observability for both constellation design and measurement planning purposes.

3:00 PM

AAS-256 : Traversing the Lagrange Point Trajectory Network Using Isolating Neighborhoods

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

Isolating blocks and isolating neighborhoods have previously been shown to be useful for computing orbits, invariant manifolds, and transit trajectories around the collinear libration points in the CRTBP. They may also be used to compute transfers between periodic and quasi-periodic orbits inside the libration point isolating invariant set using invariant manifolds. In this study, we explore the network of these connections between orbits and evaluate the cost of these transfers. We also search for sequences of transfers in this trajectory network to find transfers between specific orbits. The characteristics of these transfers are described and total maneuver costs are computed.

Orbit Determination and Estimation IV
Room: Pine, Tuesday, August 13
2:00 PM - 3:15 PM
Session Chair(s): Kyle DeMars (Texas A&M University) and Craig McLaughlin (University of Kansas Aerospace Engineering)

2:00 PM
AAS-337 : An Orbit Determination Comparison Study and Demonstration for Rendezvous and Docking in a Near Rectilinear Halo Orbit from the Lunar Surface
David Woffinden (NASA Johnson Space Center), Duane Roth (Jet Propulsion Laboratory), Juan Orphee (NASA Marshall Space Flight Center)

For the upcoming NASA Artemis III mission and those that follow, both the Human Landing System (HLS) and Orion programs are invested in understanding the impacts of ground tracking performance in supporting rendezvous and docking in a Near Rectilinear Halo Orbit (NRHO). Several critical questions must be answered to ensure mission success and crew safety and an assortment of analysis tools are being incorporated to address them. Two of these tools, LINCOV and MONTE, are currently providing program decision making results through HLS Insight, HLS NASA-collaborations, and Orion/Gateway cross-program analysis. To ensure consistency in the orbit determination performance, a comparison trade-study is performed using a low-lunar orbit to NRHO rendezvous

2:15 PM
AAS-339 : Processing Angles-Only Tracklets for Cislunar Multi-Target Tracking
Dalton Durant (The University of Texas at Austin), Andrey Popov (The University of Texas at Austin), Kyle DeMars (Texas A&M University), Renato Zanetti (Blue Origin)

This work addresses the challenge of multi-target tracking in cislunar orbits utilizing angles-only tracklets from ground-based optical telescopes. Traditional orbit determination methods rely on the batch processing of angles-only measurements into a six-dimensional state-space. These methods encounter limitations in handling nonlinearities within cislunar dynamics. To overcome these limitations, this work leverages Markov Chain Monte Carlo methods for processing angles-only tracklets in Cartesian coordinates and performs multi-target tracking with Joint Probabilistic Data Association techniques. Numerical simulations illustrate the superiority of the proposed methods in scenarios with multiple targets and increased orbital congestion. This work contributes to a comprehensive solution for angles-only multi-target tracking in complex cislunar environments.

2:30 PM

AAS-349 : Deep Space Navigation Using Occultations of Celestial X-ray Sources

Benjamin Sorge (ASTER Labs Inc.), Chuck Hisamoto (ASTER Labs, Inc.), Suneel I. Sheikh (ASTER Labs, Inc.), Benjamin Oren (ASTER Labs Inc.), Kent Wood (Technology Service Corporation (TSC)), Andrea Lommen (Haverford College), Kevin D. Anderson (ASTER Labs)

Increases to the number of future deep space missions will necessitate onboard navigation systems that provide greater vehicle autonomy. Utilization and tracking of observed celestial X-ray-emitting sources hold significant potential in facilitating increasingly independent vehicle operations. An Occulting X-ray-source Navigation (OXNAV) system is presented that employs the timing of X-ray source horizon crossings onboard a vehicle within view of a planet to improve estimated spacecraft states. Preliminary analyses of orbital trajectories with source occultations have demonstrated OXNAV's capabilities to expand mission concepts, load shed the existing DSN infrastructure, and enhance autonomous operation further into the solar system.

2:45 PM

AAS-355 : Navigation Performance Overview of Gateway During a Lunar Lander Mission

Clark Newman (a.i. solutions, Inc.), Connor Ott, Abram Aguilar (a.i. solutions, Inc.), Diane Davis (NASA Johnson Space Center)

The HLS mission timeline and perturbations are simulated considering antenna blockage to ground stations. Simulated DSN tracking data is generated and processed to produce a navigation state estimate for Orbit Maintenance Maneuver targeting. The starting epoch is varied to simulate tracking availability from structural blockage, and the amount of tracking data processed during crewed operations is reduced. Separately, the observability of perturbations in the NRHO with two-way tracking data is analyzed. The mission is simulated with imperfect \textit{a priori} knowledge of venting perturbations, and finally the estimation errors that arise from propagating an estimated state from data cutoff (DCO) to a docking event are investigated.

3:00 PM

AAS-447 : Efficient Satellite Constellation Orbit Propagation using Picard-Chebyshev Methods

David Stanley (The University of Illinois), Robyn Woollands (University of Illinois at Urbana-Champaign)

The 15th-order Gauss-Radau integrator is popular in n-body astrodynamics for its speed and stability. Deviations from the 15th-order scheme are said to increase round-off error and computation time for lower orders, and potential missed close approaches for higher orders. Our study aims to validate these claims across various orders, evaluating computation time, energy conservation, and solution discrepancies. Initial findings reveal trade-offs: Lower-order schemes demand more steps for energy conservation, increasing computational load, while higher-order schemes conserve energy better with fewer steps but require similar computation requirements. Further research will refine error predictions and explore longer integrations in complex scenarios.

Trajectory, Mission, and Maneuver Design/Optimization VI
Room: Centennial F, Tuesday, August 13
2:00 PM - 3:15 PM
Session Chair(s): Ehsan Taheri (Auburn University) and James Thorne (Institute for Defense Analyses (IDA))

2:00 PM

AAS-350 : Maneuver Planning and Analysis with Copernicus for the IM-1 Mission

James Moore (Intuitive Machines), Timothy Roorda (Intuitive Machines), Daniel Greer (Intuitive Machines), Shaun Stewart (Intuitive Machines)

Mission designers at Intuitive Machines employed NASA's Copernicus trajectory design and optimization system in multiple ways to successfully land the IM-1 mission. Engineers created preliminary Design Reference Mission (DRM) trajectories to support the design of multiple spacecraft and ground systems. Designers developed Copernicus-based maneuver-planning tools for use in pre-mission trajectory planning. Analysts developed Monte Carlo tools that deployed Copernicus to sequentially optimize mission segments under dispersed conditions. Mission operators used Copernicus to optimize individual maneuvers during the transit and descent to the lunar surface. We present a successful architecture for lunar trajectory design centered around the Copernicus system.

2:15 PM

AAS-177 : Optimal solar sail trajectories for fast deep space missions

Alesia Herasimenka (SnT, University of Luxembourg), Lamberto Dell'Elce (Inria), Andreas Hein (SnT, University of Luxembourg)

This paper proposes the calculation of optimal trajectories for a solar sail mission to deep space. Leveraging gravity and photonic assists by approaching the sun enables acceleration of a solar sail towards the farthest regions of the solar system. We address an optimal control problem while incorporating temperature constraints resulting in a combined constraint both on the state and the control of the system, utilizing multiple shooting methods. Differential continuation techniques are subsequently employed to attain feasible trajectories for poorly reflective solar sails. This analysis allows for the assessment of the mission's feasibility using an aerographene sail.

2:30 PM

AAS-393 : Reachability Study of Low-Thrust CubeSat Transfers from Gateway to Sun-Earth Orbits

Carrie Sandel (The University of Alabama), Rohan Sood (The University of Alabama)

With current plans to establish a long-term cislunar presence through NASA's lunar space station, Gateway, there is a strong interest in exploring a wide range of potential missions that either conclude at or originate from Gateway. As such, this work performs a reachability analysis of a CubeSat departing from Gateway using electric propulsion and explores mass-optimal transfers to families of L2 Lyapunov and halo orbits in the Sun-Earth system. The results of this research show that a low-thrust spacecraft can reach L2 Sun-Earth orbits after departing from Gateway with as little as 54 m/s of Delta-V.

2:45 PM

AAS-394 : Stabilized Continuation with Integrated Chebyshev Collocation for Trajectory Optimization

Anna Hagen (The University of Texas at Austin), Mihir Vedantam (The University of Texas at Austin), Maruthi R. Akella (The University of Texas at Austin), Manoranjan Majji (Texas A&M University, College Station)

This paper introduces a method for generating optimal trajectories that leverages the accuracy and computational efficiency of collocation techniques within a stabilized continuation framework. Stabilized continuation recasts boundary value problems into initial value problems that are readily solved with numerical integration techniques, thereby lending itself to optimal control. The proposed method transforms this IVP into a parameter optimization problem that is more solvable. The result is a global path approximation of each unknown state's trajectory along the continuation path in fewer integration steps. Numerical examples are provided to draw sharp contrasts and highlight the computational efficiency of the proposed algorithm.

Dynamical Systems Theory Applied to Spaceflight Problems III
Room: Centennial E , Tuesday, August 13
3:45 PM - 5:00 PM
Session Chair(s): Rodney L. Anderson (Jet Propulsion Laboratory/Caltech)

3:45 PM

AAS-361 : Back-Substitution Based Spacecraft Dynamics Modeling with Selective Configuration Space Branching

Andrew Morell (University of Colorado Boulder), Hanspeter Schaub (University of Colorado)

As modern space missions eye more ambitious goals, the complexity of their structural designs are also growing. Spacecraft components previously mounted statically to a central hub can be seen in mission concepts attached to mobile structures, and components with legacy being on mobile platforms can be seen on thinner or higher degree of freedom structures. This work considers three such categories corresponding to what modelled forces and torques drive these time varying geometries: ctuated joints, hub excited flexing, and component excited flexing. Previous developments in the first two categories are highlighted, and the third category is proposed as a previously unexplored problem.

4:00 PM

AAS-452 : Software Implementation of Frame Independent Vector and Tensor Mathematics Using Kinematics Informed Tree Topology

Cody Allard (Laboratory for Atmospheric and Space Physics - CU Boulder), João Vaz Carneiro (University of Colorado Boulder), Patrick Kenneally (Laboratory for Atmospheric and Space Physics (LASP))

When deriving equations of motion for complex systems, frame independent derivations are preferred because of the simplified mathematical formulations. When implemented in simulation software, frame relative operations are required to solve the calculations. However, it is beneficial of implementing frame independent mathematics at a certain level within the software implementation. These benefits include reduced cognitive load for the user and developers of the software, one to one mapping from documentation to software implementation, code centralization, efficient memory allocation and compact code. This paper outlines the software architecture that enables frame independent vector and tensor mathematics, and includes examples that showcase the benefits of this architecture.

4:15 PM

AAS-477 : A Flow map Parameterization Method for Quasi-periodic Orbit Computation in the Hill Restricted Four-body Problem

Damennick Henry (University of Colorado at Boulder), Daniel Scheeres (University of Colorado Boulder)

Quasi-periodic orbits are important phase space structures with many applications in astrodynamics. This paper extends flow map parameterization (FMP) methods which have enabled the rapid computation of these solutions. Specifically, an FMP algorithm is devised to compute partially elliptic tori and new robust continuation algorithms are introduced. Orbit families near Earth-Moon L1 and L2 in the Sun-Earth-Moon Hill restricted four-body problem are computed using the techniques. The increased computational efficiency allows the algorithm to continue previously studied families further and identify new orbit families that bifurcate along them.

4:30 PM

AAS-487 : Time-varying Koopman Operators meet Floquet Theory for Increased Orbit Prediction Accuracy

Damien GUEHO (Geminus.AI)

As the number of resident space objects (RSOs) increases and incidents involving potential satellite collisions escalate, the precise prediction of orbital trajectories has emerged as critical. While conventional physics-based integrators can provide insightful short-term prediction, their use for longer-time prediction (coupled with the mediocre accuracy of TLE datasets) has proven inadequate in addressing this challenge. By leveraging time-varying Koopman operators (TVKO) to model the departure dynamics from a nominal trajectory, it is possible to gain insights about higher-order dynamics from historical data, and refine orbit prediction methodologies. Floquet theory is then employed to encapsulate TVKO into a single linear time-invariant (LTI) system, allowing for more accurate long-term prediction. Datasets sourced

Orbit Determination and Estimation V
Room: Pine, Tuesday, August 13
3:45 PM - 5:00 PM
Session Chair(s): Casey Heidrich (University of Colorado Boulder) and Brandon Jones (The University of Texas at Austin)

3:45 PM

AAS-362 : A Comparison of Orbit Determination Methods in Cislunar Space

Jeremy Dening (University at Buffalo), John Crassidis (University at Buffalo, The State University of New York), Chris Nebelecky (University at Buffalo/CUBRC)

An increase in missions in the cislunar domain make orbit determination in this regime all the more important. Near-Earth active radar is mostly ineffective due to the large distances between the Earth and Moon. Optical sensing can struggle with exclusion zones where bright celestial bodies overpower the light reflected from a satellite. This study considers orbit determination of a satellite in near rectilinear halo orbit using observations collected by an observer satellite in a low-Earth orbit. Two methods are used to perform the orbit determination: batch least-squares and the Unscented Kalman Filter. The results of these are then compared for fidelity to the underlying trajectory.

4:00 PM

AAS-369 : Translunar Initial Orbit Determination through Potential Energy Gates

Stef Crum (Georgia Institute of Technology), Brian Gunter (Georgia Institute of Technology), Gregory Badura (Georgia Tech Research Institute), Alaric Gregoire (Georgia Institute of Technology)

This paper proposes an architecture to complete Initial Orbit Determination on Low-Thrust translunar satellites through the usage of potential energy gates. The analysis uses a high-fidelity dynamical model to complete orbit determination of real missions as well as generated missions. It proposes an alternate architecture that has the potential to no longer require constant custody of low-energy translunar orbits.

4:15 PM

AAS-397 : A novel pointing technique for the enhancement of tropospheric delay calibration system performances

David Bernacchia (University of Bologna), Riccardo Lasagni Manghi (Alma Mater Studiorum - Università di Bologna), Marco Zannoni (University of Bologna), Paolo Tortora (Alma Mater Studiorum - Università di Bologna), Jose Villalvilla (ESA - ESOC), Javier De Vicente (ESA - ESOC), Paolo Cappuccio (Sapienza University of Rome), Luciano Iess (Sapienza University of Rome)

The beam-crossing is a novel radiometer pointing technique aimed at the improvement of tropospheric noise calibration performances of the water vapor radiometer installed close to the ESA's deep space ground station DSA-3. In this work we report the findings of the first-ever testing of this technique. We analyzed the behaviour of the beam-crossing through the analysis of the Doppler residuals extracted from the orbit determination process performed on data collected during a dedicated tracking campaign. Despite the limitations of the test, this technique showed interesting features that will be reported in the full paper.

4:30 PM

AAS-406 : Hera Orbit Determination Covariance Analysis of Didymos Binary Asteroid with the Full Two-Body Problem

Edoardo Gramigna (University of Bologna), Riccardo Lasagni Manghi (Alma Mater Studiorum - Università di Bologna), Marco Zannoni (University of Bologna), Paolo Tortora (Alma Mater Studiorum - Università di Bologna), Michalis Gaitanas (Aristotle University of Thessaloniki), Ioannis Gkolias (Aristotle University of Thessaloniki), Kleomenis Tsiganis (Aristotle University of Thessaloniki), Ryan Park (Jet Propulsion Laboratory), Alex Meyer (University of Colorado Boulder), Petr Pravec (Astronomical Institute, Academy of Sciences of the Czech Republic)

ESA's Hera mission will complement NASA's DART mission in studying the Didymos binary asteroid system and validating the kinetic impactor technique for planetary defense. Hera's radio science experiment aims to estimate key physical parameters of the system after DART's impact. This work focuses on implementing the Full Two-Body Problem (F2BP) model into JPL's MONTE S/W to perform an accurate covariance analysis. Comparison of the expected results with the ones obtained using standard radio science models indicates similar performances for non-chaotic post-impact scenarios; conversely, chaotic scenarios present more significant challenges, which will be addressed in our work.

Rendezvous, Relative Motion, and Proximity Operations I
Room: Pinon, Tuesday, August 13
3:45 PM - 5:00 PM
Session Chair(s): Anubhav Gupta (In Orbit Aerospace, Inc. & University of Colorado Boulder) and Mark Muktoyuk (Astroscale US)

3:45 PM
AAS-200 : Factor Graph-Based Active SLAM for Spacecraft Proximity Operations
Lorenzo Ticozzi (Georgia Institute of Technology), Panagiotis Tsiotras (Georgia Institute of Technology)

This paper considers an agent satellite equipped with a monocular camera navigating in proximity of a client spacecraft. The goal of the agent is to understand its surroundings and localize itself using camera images. We frame this problem as smoothing-based simultaneous localization and mapping (SLAM), represented through a factor graph, to estimate the spacecraft's trajectory and map its environment. Our method innovatively integrates estimation and planning by adopting an information-theoretic approach to select attitude trajectories that optimize the belief state evolution. Through numerical simulations, we show that our strategy outperforms passive sensing techniques achieving lower uncertainty and greater accuracy.

4:00 PM
AAS-290 : Fuel-Optimal Multi-Agent Operations with Path Inequality Constraints
Ruthvik Bommena (University of Illinois Urbana-Champaign), Robyn Woollands (University of Illinois at Urbana-Champaign)

The increasing focus on sustainable spacecraft operations like on-orbit serving and manufacturing necessitates technological advances. Multi-agent spacecraft teams are essential for autonomous in-space servicing missions, requiring fuel-efficient operations and adherence to various path constraints. This paper introduces a novel method for global multi-agent path-constrained trajectory optimization using indirect techniques. The approach ensures local optimality and constraint satisfaction by formulating trajectory planning as a single indirect optimal control problem. Simulations use a unique dynamical model and utilize hyperbolic tangent functions and continuation for smoothing constraint transitions. Algorithm’s efficacy and versatility is demonstrated in various mission configurations and different path constraint scenarios.

4:15 PM
AAS-306 : Robust Trajectory Planning for Close Proximity Spacecraft Operations
Zachary Preissman (Pennsylvania State University), Puneet Singla (The Pennsylvania State University), Maruthi R. Akella (The University of Texas at Austin), Sharad Sharan (Pennsylvania State University)

A regularized control procedure is applied to solve the minimum-time optimal spacecraft docking problem with control constraints. The fully nonlinear Clohessy-Wiltshire equations of motion for relative motion dynamics are introduced. The classical formulation for bang/bang singular control is derived along with a discussion as to why we wish to investigate alternative approaches. The Generalized Control Regularization Method is introduced as our alternative approach to alleviate the difficulties that arise in the classical formulation. This alternative method provides numerical stability and eliminates ambiguity in the control law. The new control law is then adapted to meet path constraints in the trajectory. A novel control law given path and control limitations is presented.

4:30 PM

AAS-314 : Relative Navigation Informed Formation Configuration and Station-keeping in the Earth-Moon-Sun System

Fouad Khoury (Johns Hopkins Applied Physics Laboratory), Rolfe Power (Purdue University), Pradipto Ghosh (Johns Hopkins University Applied Physics Lab), Juan Ojeda Romero (Johns Hopkins University Applied Physics Laboratory)

While considering formation flying missions in Cislunar space, this investigation develops relative motion GNC (Guidance, Navigation, and Control) strategies to coordinate multiple spacecraft in the Earth-Moon-Sun system. Relative equations of motion (EOMs) characterizing the dynamics between two spacecraft in a chief-deputy configuration are leveraged in the context of the Bicircular Restricted Four-Body Problem (BCRFBP). These EOMs are then utilized as part of a guidance algorithm informed by a relative navigation strategy using simulated onboard measurements subject to solar visibility constraints. All of these strategies are implemented to demonstrate formation configuration and station-keeping along an L_2 halo orbit in the BCRFBP.

4:45 PM

AAS-338 : Co-Optimization of Navigation System Requirements and Trajectory Design Using a Sweeping Gradient Method and Linear Covariance Analysis

Benjamin Margolis (NASA Ames Research Center), **David Woffinden** (NASA Johnson Space Center)

We describe the application of a sweeping gradient method for ordinary differential equations with events (SGM) and linear covariance analysis (LinCov) to the co-optimization of navigation system requirement generation and robust trajectory design. SGM is a method for computing the gradient of trajectory analyses defined by performance indices over initial value problems with events with respect to static parameters. LinCov is an analytic technique for predicting stochastic behavior of dynamical systems. In this paper, we formulate the required models to apply the combined SGM and LinCov techniques to a Near-Rectilienar Halo Orbit rendezvous approach scenario and show results for a several of intermediate problems.

Trajectory, Mission, Maneuver and Design/Optimization VII
Room: Centennial F, Tuesday, August 13
3:45 PM - 5:00 PM
Session Chair(s): Robert Melton (Pennsylvania State University) and James Thorne (Institute for Defense Analyses (IDA))

3:45 PM
AAS-383 : Robust Low-Thrust Trajectory Correction Planning Under Uncertainty: Primer Vector Theory Approach
Yanis Sidhoum (Purdue University), Kenshiro Oguri (Purdue University)

This paper presents a robust spacecraft trajectory correction framework for safe low-thrust trajectory under uncertainty using indirect method. We utilize the primer vector theory to design a sequence of control policies that map the state deviations to trajectory correction maneuvers (TCMs) while minimizing the state covariance at critical phases (e.g., on the target and/or close flyby). The developed framework incorporates the stochastic effects of imperfect state knowledge, partially known dynamical environments, and control execution errors into the mission design process, enabling fast and efficient flight path control while satisfying mission constraints under operational uncertainty.

4:00 PM
AAS-390 : Pathfinding for Pump-Down Flyby Tours at Saturn using Directed Graphs
William Brandenburg (University of Texas at Austin Department of Aerospace Engineering and Engineering Mechanics), Ryan Russell (The University of Texas at Austin), Matthew Shaw (Lockheed Martin Corporation)

A new method is developed using a low-dimensioned directed graph of the pump-down tour space of a planetary moon. The graph and its discretized information on the moon's resonant and non-resonant transfer space are used to efficiently evaluate pump-down transfer sequences for time of flight and maneuver costs. A Pareto front is identified for the best sequences in a patched conics model, and the associated solutions are converted to integrated trajectories in a high-fidelity model. The full process is automated and enables a thorough search of the design space resulting in families of optimized high-fidelity pump-down flyby tour trajectories

4:15 PM
AAS-395 : Optimizing the Placement and Low-Thrust Maneuvers of Multi-Purpose Orbiters around Venus
Trupti Gosavi (West Virginia University), Dominic Amato (West Virginia University), Jacob Swecker (West Virginia University), Hang Woon Lee (West Virginia University)

A novel concept of operations (CONOPS) to study the atmospheric and geological state of Venus using multi-purpose orbiters is discussed in this work. This CONOPS is enabled by a framework consisting of two optimization formulations. First, the problem of designing an RO constellation of a set number of orbiters to maximize spatial coverage is solved using a novel formulation. Secondly, to facilitate near-surface probing of the atmosphere using a balloon, low-thrust optimization is used to reconfigure the RO constellation so that the visibility of the balloon is maximized. A case study demonstrating the application of the framework to study volcanism on Venus is discussed.

4:30 PM

AAS-425 : Europa Clipper Mission Analysis: A Flexible Graph-Based Search Automaton for Gravity-Assist Trajectory Design

Donald Ellison (The Johns Hopkins University Applied Physics Laboratory), Christopher Scott (The Johns Hopkins University Applied Physics Laboratory)

NASA's next flagship planetary science mission, Europa Clipper, is scheduled to launch in October 2024. After a 5.5 year cruise to Jupiter, the spacecraft must insert into orbit and perform an orbital period/energy reduction campaign. This period, known as the pump down, is a complex combinatorial multiple gravity-assist pathfinding problem that is solved with a software automaton that represents the problem space using a multi-tree data structure. The architecture of this search framework is described as well as how it was applied to the Clipper pump down problem. It's flexibility is also demonstrated on selected other complex multiple gravity-assist problems.

4:45 PM

AAS-433 : Europa Clipper Mission Analysis: Pump Down Trajectory Design

Christopher Scott (The Johns Hopkins University Applied Physics Laboratory), Donald Ellison (The Johns Hopkins University Applied Physics Laboratory), Kevin Bokelmann (The Johns Hopkins University Applied Physics Laboratory), Martin Ozimek (The Johns Hopkins University Applied Physics Laboratory), Etienne Pellegrini (Jet Propulsion Laboratory), Stefano Campagnola (Jet Propulsion Laboratory), Brent Buffington (JPL)

The Europa Clipper spacecraft will launch in October of 2024 and arrive at Jupiter in April of 2030 after a gravity assist sequence involving Earth and Mars. This paper outlines the design philosophy, process, and constraints associated with the robust pump down trajectory design envelope. The design seeks the usual efficiencies involving propellant and time-of-flight while providing mission robustness, overall cost savings, and early science data collection opportunities. Mathematically, the design is cast as a multi-objective, multi-agent optimization problem with constraints.

Cislunar Astrodynamics V
Room: Pinon, Wednesday, August 14
8:30 AM - 10:00 AM
Session Chair(s): Brian Gunter (Georgia Institute of Technology)

8:30 AM
AAS-321 : Preliminary Design Strategy for Long-Term Loitering Orbits in Cislunar Space
Mitchell Dominguez (Purdue University), Kathleen C. Howell (Purdue University)

Cislunar hubs such as the NASA Gateway facility, among others, are designed to interface with visiting spacecraft. Operational considerations, however, inevitably require visitors to loiter while other spacecraft complete their objectives. This investigation introduces an approach for designing long-duration loitering trajectories in the Circular Restricted Three Body Problem (CR3BP) by leveraging the hub orbit center manifold. From the perspective of a linear analysis, the solution space for ballistic loitering orbits under relative distance constraints is characterized. Sample loitering orbits and subsequent rendezvous maneuvers are evaluated near hub orbits with varying stability characteristics, demonstrating general applicability.

8:45 AM
AAS-326 : Jettisons from the Gateway Near Rectilinear Halo Orbit to Heliocentric Space: Applications and Practical Considerations
Diane Davis (NASA Johnson Space Center), Gavin Brown (University of Colorado Boulder), Stephen Scheuerle (Purdue University), Emily Zimovan-Spreen (NASA Johnson Space Center), Kathleen C. Howell (Purdue University)

Objects deployed from a Near Rectilinear Halo Orbit (NRHO) experience simultaneous gravitational forces from the Moon, the Earth, and the Sun, and post-deployment behavior is complex. This investigation considers jettison trajectory design for objects deployed from the Gateway NRHO with varying capabilities. Recontact risk with the Gateway as each object departs the lunar vicinity is explored, and both the immediate destination and the long-term fate of the deployed objects are assessed. Escapes to interior and exterior heliocentric orbits are considered in both nominal and dispersed environments, each over a wide range of jettison conditions, including Δv magnitude and epoch.

9:00 AM
AAS-368 : Resonance Widths, Chaotic Zones, and Transport in Cislunar Space
Anjali Rawat (Virginia Tech), Bhanu Kumar (Heidelberg University), Aaron J. Rosengren (University of California San Diego), Shane Ross (Virginia Tech)

Lunar mean-motion resonances (MMRs) significantly shape cislunar dynamics beyond GEO forming stable-unstable pairs, with corresponding intermingled chaotic and regular regions. The resonance zone is rigorously defined using the separatrix of unstable resonant periodic orbits surrounding stable quasi-periodic regions. Our study leverages the restricted three-body problem to measure the (stable) widths and (unstable overlap) zones of 2:1 and 3:1 MMRs across various Jacobi constants, employing a Poincaré map at osculating orbit perigee and presenting findings in Delaunay variables. An analysis of the semi-major axis versus eccentricity plane reveals broader regions of resonance influence than those predicted by analytical models.

9:15 AM

AAS-379 : Sequential Chance-Constrained Covariance Steering for Robust Cislunar Trajectory Design under Uncertainties

Naoya Kumagai (Purdue University), Kenshiro Oguri (Purdue University)

Operations in space are influenced by various uncertainties. Although mission design has traditionally incorporated heuristics to mitigate these effects, it is unclear whether this will scale in the cislunar region, which features locally chaotic nonlinear dynamics and involves frequent lunar flybys. This paper applies chance-constrained covariance steering to design a safety-guaranteed optimal control policy that accounts for the underlying uncertainty models. The framework allows faster computation and lossless covariance propagation than existing methods. Post-analyzing the control policy provides insight into the yet unsolved continuous-time, closed-loop, nonlinear, stochastic minimum-fuel problem. We demonstrate the algorithm on transfers in the Earth-Moon Circular-Restricted Three-Body Problem.

9:30 AM

AAS-386 : Transfer Strategies for Long-Term Loitering in the Vicinity of Near Rectilinear Halo Orbits

Abram Aguilar (a.i. solutions, Inc.), Brian McCarthy (a.i. solutions, Inc), Rohan Sood (The University of Alabama)

With NASA's plans to operate a crewed space station, Gateway, in an Earth-Moon 9:2 L2 southern NRHO, crewed-vehicle safety must be the priority. While HLS, Orion, transporters, resupply vehicles, or CubeSat deployments are in the vicinity of Gateway, certain spacecraft may need to maintain a loitering trajectory relative to the Gateway. While short-term loitering about the Gateway as a reference is of interest, long-term loitering configurations must be considered as well. These long-term configurations can be achieved by placing spacecraft in orbits nearby the Gateway NRHO.

Dynamical Systems Theory Applied to Spaceflight Problems IV
Room: Centennial E , Wednesday, August 14
8:30 AM - 10:00 AM
Session Chair(s): Annika Anderson (Embry-Riddle Aeronautical University) and David Canales Garcia (Embry-Riddle Aeronautical University)

8:30 AM
AAS-270 : A Numerical Method for Computing the State Transition Matrix Using Poincare Integral Invariants
Michael Shoemaker (NASA GSFC), Kyle Hughes (NASA Goddard Space Flight Center)

The Poincare integral invariants describe the volumes of sets in Hamiltonian phase space. We use these invariants to derive a new numerical procedure for obtaining the state transition matrix (STM), which can be applied to both conservative and nonconservative systems. The method is analogous to a finite difference approximation of the STM, where perturbed states are numerically propagated along with the reference trajectory. We discuss the mathematical similarities between this new STM and existing methods, show numerical results for orbital motion and uncertainty propagation, and discuss new insights afforded by the Hamiltonian properties of phase flow.

8:45 AM
AAS-277 : Characterization of Periodic Angular Velocity Trajectories in Inertial Space for Torque Free Symmetric Rigid Bodies using Split Derivatives
George Davailus (Northrop Grumman)

The nonlinear nature of 6-DOF differential equations makes robustness prediction of aerospace vehicle GNC systems operating in the presence of noisy inputs time consuming. This paper will build on prior research involving a transformation of the kinematic and kinetic rotational 6-DOF equations from nonlinear to linear time varying and a further transformation to linear time invariant. This was accomplished by splitting the rotational parameters in two, with the components being represented in the inertial and rotating coordinate systems respectively. Two quaternion exponentials were used to separate the rotational dynamics into different coordinate systems. Criterea for determining whether the overall dynamics are periodic are based on a comparison of the quaternion exponentials.

9:00 AM
AAS-278 : Local Orbital Element Toolkit in Cislunar Space
Luke Peterson (University of Colorado Boulder), Daniel Scheeres (University of Colorado Boulder)

In order to track orbits in cislunar space, predict where they will naturally move over time, and identify where unbounded trajectories came from, one may consider local action-angle orbital elements–coordinates which relate a spacecraft state to specific trajectories and exist in approximately integrable regions of the Earth-Moon circular restricted 3-body problem. In this work, we extend the local action-angle orbital element framework to include (quasi-)halo orbits via computation of a resonant normal form. We demonstrate results around Earth-Moon L1 and L2, parameterizing (quasi-)periodic orbits and their (un)stable manifolds. The programs to compute local orbital elements are packaged into a MATLAB toolkit.

9:15 AM
AAS-292 : Closed-Loop Nonlinear Optimal Control for Station-Keeping in Low Earth Orbits
Dennis Yang (Drexel University)

We study the station-keeping problem for satellites in near-circular, low Earth orbits under the influence of atmospheric drag and the Earth's oblateness. The objective is to maintain the orbit's low eccentricity and the satellite's tracking of its angular slot along the orbit while the orbital plane is allowed to drift due to the effect of the Earth's oblateness. Via the stable manifold approach, we obtain a closed-loop nonlinear optimal control law for this problem with thrust magnitude constraint.

9:30 AM
AAS-308 : Data-Driven Representation of High-dimensional Invariant Manifolds by Tensor-Based Dynamic Mode Decomposition
Mai Bando (Kyushu University), Keisuke Murayama (Kyushu University), Shinji Hokamoto (Kyushu University)

Several approaches have been studied to represent invariant manifolds of nonlinear dynamical systems in semianalytical form for which analytical solutions do not exist. In this study, the Koopman operator, a finite-dimensional approximation of linear operator which describes the evolution of the nonlinear differential equations of invariant manifolds from data, is used to approximate invariant manifolds in the form of solutions of linear differential equations. Tensor-train format and dynamic mode decomposition are utilized to obtain a simple function representation of those objects. The proposed method is demonstrated through applications.

9:45 AM
AAS-352 : An architectural concept for multibody dynamical systems trajectory design with STK Astrogator
Cody Short (AGI (Ansys Government Initiatives)), Marisa Exnicious (Ansys Government Initiatives (AGI)), Giuseppe Corrao (Ansys), Linda Kay-Bunnell (AGI, an Ansys Company), Nathaniel Kinzly (AGI, an Ansys Company), Doug Cather (AGI, an Ansys Company)

Multibody dynamical systems approaches to spacecraft trajectory design, analysis and operations are becoming increasingly relevant as focus in the space industry shifts back to the Moon. The dynamics associated with cislunar motion reflect characteristics that may be unfamiliar to space professionals first coming to the domain. Effective tooling that incorporates the associated multibody approaches enable engineers and operators to become effective more quickly and accomplish their mission. This paper discusses a proposed framework for multibody dynamical systems approaches for use within the Ansys Systems Tool Kit. The framework leverages Astrogator, Satellite Collections, the Component Browser and attendant internal utility algorithms.

Satellite Constellations and Formations
Room: Centennial F, Wednesday, August 14
8:30 AM - 10:00 AM
Session Chair(s): Yashica Khatri (NorthStar Earth & Space) and Christopher Roscoe (Ten One Aerospace)

8:30 AM

AAS-165 : Analysis and Design of Satellite Constellation Spare Strategy Using Markov Chain

Seungyeop Han (Georgia Institute of Technology), Takumi Noro (Mitsubishi Electric Advanced Technology R&D Center), Koki Ho (Georgia Institute of Technology)

This paper introduces the analysis and design method of an optimal spare management policy using Markov chain for a large-scale satellite constellation. We propose the analysis methodology of spare strategy with a multi-echelon (Q,r) inventory control model using Markov chain, and review two different spare strategies: direct resupply, which inserts spares directly into the constellation orbit using launch vehicles; and indirect resupply, which inserts spares into parking orbits before transferring them to the constellation orbit.

8:45 AM

AAS-268 : Orbital stability analysis and control of a three-satellite constellation considering artificial and natural equilibrium points

Ryan Gast (University of Oklahoma), Diogo Merguizo Sanchez (The University of Oklahoma)

The orbital configuration and stability of a three-satellite constellation with two satellites placed at the Lagrangian triangular equilibrium points and one satellite placed at an artificial equilibrium point (AEP) are investigated. In this configuration, the relative distance between the three satellites is kept at approximately 2.7 10^8 km. Different configurations for the satellite constellation will be explored. The results from this work can be used to build a very large laser interferometer space antenna (VLISA) with a desired science orbit of at least five years.

9:00 AM

AAS-365 : Flight Path Control Error Analysis for the HelioSwarm Observatory

Stephen West (Space Exploration Engineering), Marissa Intelisano (Space Exploration Engineering (SEE)), Paul Levinson-Muth (Millennium Engineering and Integration), Lisa Policastri (Space Exploration Engineering, LLC)

The HelioSwarm Observatory requires specific geometries be formed by the nine satellites in the swarm to resolve different scales of solar wind turbulence. Maneuver execution and state estimation drive flight path control errors that could disrupt the swarm geometry. Using a Monte-Carlo analysis, flight path control errors for dispersed trajectories were generated and the impact to science performance and other mission constraints evaluated. The results highlight the unique aspects of swarm-type multi-satellite missions in terms of maneuver planning and error tolerance.

9:15 AM

AAS-385 : Design of Safety Procedures for a Multi-Satellite Formation Using a Continuous Control Scheme

Francesca Scala (German Aerospace Center (DLR)), Gerhard Krieger (German Aerospace Center), Michelangelo Villano (German Aerospace Center (DLR))

The concept of multiple satellites in formation represents a significant advancement in enhancing the capabilities of synthetic aperture radar (SAR) interferometry. Maintaining the correct baseline and a safe configuration among the vehicles is vital for high-resolution across-track SAR interferometry missions. This study focuses on across-track single-pass interferometry based on fixed time-invariant baselines, and introduces a novel guidance and control strategy specifically designed to address safety procedures in case of off-nominal onboard conditions. The research examines the capability for rapid formation reconfiguration to enter the safe mode in terms of minimum propellant consumption, including scenarios with engine failures.

9:30 AM

AAS-471 : Navigation and Control Performance of a Distributed Component Telescope in a Highly Eccentric Orbit

Kyle Rankin (New Mexico State University), John Krizmanic (Goddard Spaceflight Center – University of Maryland), Hyeongjun Park (New Mexico State University), Neerav Shah, Steven Stochaj (New Mexico State University)

Distributed component telescopes where the optical components are split between multiple spacecraft promise to provide orders of magnitude improvements in the performance of future generation of space telescopes. To realize these capabilities, precision formation flying techniques have been developed to maintain the position of these telescope components with respect to each other in inertial space. This paper shows the results of both a PID based, and a shooting method-based controller with particular emphasis on their impacts to propellant consumption. This includes utilizing relatively low accuracy GPS based navigation when operating above the GPS constellation in the controller solution.

9:45 AM

AAS-490 : Collocation Design of an Inclined GSO with an Equatorial GSO Spacecraft

Gurpreet Singh (ISRO)

Longitude slots at geostationary height are limited and to optimal use the available space, space-faring nations park more than one spacecraft at the allocated longitude, better known as collocation. Various methods exist to collocate two spacecraft in equatorial geosynchronous orbits (eGSO), and the problem becomes intriguing when one of the collocated spacecraft needs to be in inclined GSO (iGSO) . The analysis shows that the collocation geometry between the iGSO and eGSO pairs fails for a general strategy. We present an approach to have an optimal choice of RAAN for the iGSO spacecraft to have a maneuver-free collocation for the iGSO with natural perturbations alone.

Cislunar Astrodynamics VI
Room: Pinon, Wednesday, August 14
10:30 AM - 12:30 PM
Session Chair(s): Dhruv Jain (Kayhan Space)

10:30 AM
AAS-423 : Derivation and Simulation of User Scenarios for Lunar Navigation Satellite Systems
Mark Hartigan (Georgia Institute of Technology), E. Glenn Lightsey (Georgia Institute of Technology)

Lunar Navigation Satellite Systems (LNSS) are actively being developed by international agencies and private enterprise alike to provide position, navigation, timing, and communications to the growing population of lunar users. This work focuses on demonstrating end-user performance for a variety of lunar use cases -- entry, descent, and landing and extra-vehicular activity by astronauts, among others. Provided are derivations and navigation simulations for these use cases using techniques such as trilateration, joint doppler and ranging, and various Kalman filtering methods. The tools developed in this research can be used by LNSS designers to help determine effective constellation capability.

10:45 AM
AAS-430 : Stationkeeping For Transition Region Earth-Moon Halo Orbits
Sandeep Baskar (Advanced Space LLC), Ethan Kayser (Advanced Space, LLC), Matthew Popplewell (Advanced Space), Matthew Bolliger (Advanced Space), Liam Fahey (Purdue University)

Traditional stationkeeping methods for halo orbits involve targeting schemes that leverage the symmetric geometry of these trajectories in the Earth-Moon rotating frame (y=0 crossing or x-plane control) or leveraging linearization with assumptions from the Circularly-Restricted Three-Body Problem (CR3BP) (Floquet Mode). Translating these methods to more unstable transition region halo orbits in an ephemeris model yielded inadequate orbit maintenance under external perturbations reasonably seen during flight. This study will use an extension of a y=0 crossing method to optimize orbit maintenance maneuvers (OMMs) to stay bounded in a 3:1 L2 Halo Orbit with these aformentioned perturbations.

11:00 AM
AAS-437 : A Framework for Moving ARTEMIS Abort Trajectories from the CR3BP to a High-Fidelity Ephemeris Model
Daniel Owen (Advanced Space), Brian McCarthy (a.i. solutions, Inc), Matthew Bolliger (Advanced Space), Galen Savidge (Ann & H.J. Smead Department of Aerospace Engineering Sciences at CU Boulder), Aurelie Heritier (OneWeb)

This paper describes a framework for taking an initial abort trajectory in the Earth-Moon Circular Restricted Three Body Problem (CR3BP) to a high-fidelity ephemeris model which can be used for flight operations for the NASA Artemis program. The initial trajectory is turned into a family of abort trajectories scanned across multiple parameters using continuation methods in the CR3BP. This family is then transcribed to to an ephemeris model and fed into Copernicus to create a set of ΔV optimized, high-fidelity trajectories. A specific category of aborts is highlighted from the Artemis I and III missions.

11:15 AM

AAS-443 : Observing the Cislunar Surveillance Cone from Synodic Resonant Orbit Constellations

Noah Sadaka (Purdue University), Maaninee Gupta (Purdue University), Kathleen C. Howell (Purdue University), Carolin Frueh (Purdue University)

Space situational awareness is a priority to enable the development of the cislunar region. The 30-degree cone with vertex at the Earth and opening towards the Moon is identified as a region requiring frequent visibility. Constellations of sidereal resonant orbits with a synodic resonance overlap in the Circular Restricted Three-Body Problem are identified as possessing repeating geometries with the Sun and the surveillance cone. Visibility of the interior cone by the constellation is examined to evaluate the constellation's surveillance characteristics. Several orbits with differing visibility region properties are paired to permit comprehensive surveillance of the cone.

11:30 AM

AAS-479 : Exploring an AI/ML approach to automating the transition from the circular restricted three-body problem to higher-fidelity solutions, Part 1

Marisa Exnicious (Ansys Government Initiatives (AGI)), Cody Short (AGI (Ansys Government Initiatives)), Teresa Brooks-Mejia (Ansys Government Initiatives (AGI)), Doug Cather (AGI, an Ansys Company)

The circular restricted three-body problem (CR3BP) is a foundational model for trajectory design in multibody environments. However, there is a growing need to model orbits using higher-fidelity perturbations in order to reflect real-life behaviors. The conversion between these dynamical models is non-trivial. This paper proposes a solution using AI/ML to predict whether an orbit in the CR3BP has a valid counterpart in higher-fidelity models, using the elliptic restricted three-body problem (ER3BP) as an intermediary. This preliminary investigation will encompass the generation of a dataset of successful transformations to be used as training data in an AI/ML algorithm to come.

11:45 AM

AAS-483 : Dynamical Model Fidelity Measures for Cislunar Astrodynamics

Quintin Nelson (Texas A&M University), Manoranjan Majji (Texas A&M University, College Station)

Model order reduction is important in engineering applications. Methods to quantify model fidelity in reduced order models provide useful tools to perform engineering tradeoffs in elements of space system design. This paper investigates the utility of the Vinnicombe gap metric on the model fidelity quantification of uncertain dynamical systems governing the mechanics of spacecraft in a multi-body gravitational environment. Time and frequency domain approaches to evaluate the gap metric for various problems in cislunar astrodynamics are derived and implemented.

12:00 PM

AAS-486 : Analysis of Non-Isotropic Estimation Causes for Cislunar State SSA

Kullen Waggoner (Air Force Institute of Technology)

This research investigates the challenges of determining the x-coordinate location of a resident space object in cislunar space. The non-isentropic nature of the es- timation appears to be the result of both the dynamics of the CR3BP in the corridor between the Earth and Moon between the L4 and L5 Lagrange point and the ob- servability of the measurements, particularly when using passive RF TDOA and FDOA and electro-optical.

12:15 PM

AAS-228 : Lunar ephemeris, rotation, and gravity field

Ryan Park (Jet Propulsion Laboratory), Alex Konopliv (NASA / Caltech JPL), Dale Boggs (NASA / Caltech JPL)

The latest JPL planetary and lunar ephemerides, DE440, was released in 2020, which provides the position and velocity of the eight planets and the Moon as well as Moon's body-fixed orientation with respect to the International Celestial Reference Frame (ICRF). We present the accuracy of Moon's orbit and rotation for the next decade in the context of various use cases, including cruise, in-orbit, and surface operations. As part of the DE440 release, two lunar body-fixed reference frames were provided, called Principal Axis (PA) frame and Mean-Earth (ME) frame. We also present lunar gravity fields derived using the GRAIL data that are tied to PA and ME frames for spacecraft operations

Trajectory, Mission, and Maneuver Design/Optimization VIII
Room: Centennial F, Wednesday, August 14
10:30 AM - 12:30 PM
Session Chair(s): Matthew Shaw (Lockheed Martin Corporation) and Daniel Wibben (KinetX, Inc.)

10:30 AM

AAS-442 : Advancements in Particle Swarm Optimization-Based Co-State Initialization for Spiral Trajectory Optimization in Cislunar Mission Design

Grant Hecht (University at Buffalo), Eleonora Botta (University at Buffalo)

A co-state initialization methodology employing the Particle Swarm Optimization (PSO) algorithm is proposed for solving low-thrust spiral trajectory optimization problems with the Circular Restricted Three Body Problem (CRTBP) model. The proposed methodology builds upon existing PSO-based co-state initialization methods to facilitate the computation of optimal spiral transfers for acceleration levels less than 3 x 10^{-4} m/s^2 without a user-provided guess. The methodology is applied to compute both minimum-time and minimum-fuel transfers from a Geostationary Transfer orbit (GTO) to periodic orbits, or their associated invariant manifolds, within the cislunar regime.

10:45 AM

AAS-453 : Intermediate models for transitioning patched conic gravity-assist tours to high-fidelity

Chun-Yi Wu (The University of Texas at Austin), Ryan Russell (The University of Texas at Austin)

Techniques are presented to facilitate the transition between low- and high-fidelity models, motivated by the challenge of generating mission-ready trajectories for long-duration multi-body flyby tours. Intermediate models are utilized, including a medium-fidelity correction step during pathfinding; and a zero-sphere-of-influence (zSOI) preliminary step and flyby continuation method during the tour optimization. An automated initial guess generator for the high-dimensioned multiple-shooting problem is also developed, with customizations including leg lengths and maneuver placements. Convergence behavior improvements are illustrated using different combinations of these intermediate models on several example flyby tours.

11:00 AM

AAS-466 : Cislunar Orbit Transfer Analysis Using Multicriteria Considerations

Jeremy Dening (University at Buffalo), Chris Nebelecky (University at Buffalo/CUBRC), John Crassidis (University at Buffalo, The State University of New York), Moises Sudit (University at Buffalo, The State University of New York)

For many satellite missions, fuel consumption is a primary consideration when assessing potential transfer orbits. However, for cislunar orbits where Δv values to maneuver are relatively low, additional factors may be of higher relative importance. This paper presents a method, based on an Analytic Hierarchy Process to assess transfer orbits in cislunar space when multiple, possible competing criteria are considered. Simulation results for a cislunar scenario of a transfer between near rectilinear halo orbits is considered. Results for the fusion are displayed using heat maps which enable visual inspection of the assessed best transfer options.

11:15 AM

AAS-473 : Stochastic Trajectory and Controller Optimization via Optimal Recovery Diffusion Control

Akan Selim (Georgia Institute of Technology), Ibrahim Ozkol (Aviation Institute, Istanbul Technical University), Emre Koyuncu (Aviation Institute, Istanbul Technical University)

A novel computational framework for stochastic trajectory optimization is presented by integrating transcription-based methods with Interacting Particle Solutions. A novel controller called recovery diffusion control is introduced for distribution steering by leveraging the gradient-log of the probability density function. Unlike conventional approaches, the framework employs the Fokker-Planck equation for accurate propagation of non-Gaussian uncertainties for long flight durations. A benchmark Mars landing guidance problem is formulated as a stochastic optimal control and the framework is tested with Monte-Carlo analysis.

11:30 AM

AAS-484 : Orthogonal Approximation of Extremal Field Maps

Austin Widmer (Texas A&M), Thomas Ahrens (Texas A&M University), John L. Junkins (Texas A&M University)

Orthogonal polynomial approximations are used to build extremal field maps that interpolate solutions to optimal control problems in multi-variable systems. Optimal control problems are solved via an indirect integral collocation method using Chebyshev polynomials, yielding improved accuracy and significant runtime speedups. Solutions in the high-dimensional parameter space are sampled at nodes which yield discrete orthogonality conditions. Extremal field maps are found in a computationally efficient manner as the trivial to invert least-squares solution which approximates all possible parameters, and the error between node points is quantified. Continuous low-thrust trajectories for orbit transfers in single and multi-body dynamical systems are computed.

11:45 AM

AAS-220 : Analysis of Robust Low Thrust Trajectories For The Power & Propulsion Element to Earth-Moon L2 Southern Near Rectilinear Halo Orbit

Amlan Sinha (Princeton University), Ryne Beeson (Princeton University)

With the burgeoning interest in cislunar missions in the coming years, the reliance on low-thrust (LT) propulsion systems is becoming increasingly significant. LT propulsion systems are susceptible to unforeseen thruster outages or missed thrust events (MTEs), underscoring the necessity for designing trajectories that are robust to MTEs, particularly to ensure the success of critical mission components. This study focuses on the design and analysis of minimum-fuel and minimum-time robust transfer trajectories from a Medium Earth Orbit to the Earth-Moon L2 Southern Near Rectilinear Halo Orbit for the Lunar Gateway's Power and Propulsion Element.

12:00 PM

AAS-493 : Meshing of High-Dimensional Toroidal Manifolds from Quasi-Periodic Three-Body Problem Dynamics using Parameterization via Discrete One-Forms

Dante Basile (Purdue University), Xavier Tricoche (Purdue University)

High-dimensional visual computer models are poised to revolutionize the space mission design process. Leveraging the dynamics of the circular restricted three-body problem (CR3BP) for trajectory design is essential because reducing fuel consumption increases scientific payload capacity. The dynamics of the CR3BP predict ballistic trajectories along surface manifolds with 2-torus topology. In the spatial CR3BP, these manifolds exist in a 6D phase space, making it difficult to represent them with insightful visualizations. To address this challenge, we present a meshing technique which allows topologically accurate modelling and intuitive visualization of toroidal manifolds in arbitrarily high-dimensional embedding spaces.

12:15 PM

AAS-499 : Optimization-Based Phase-Constrained Station-Keeping Control on Libration Point Orbit

Yuri Shimane (Georgia Institute of Technology), Koki Ho (Georgia Institute of Technology), Avishai Weiss (MERL)

In this work, an optimization-based station-keeping algorithm for libration point orbits (LPO) based on the xz-plane crossing control technique is conceived. The optimization problem is cast as a sequential quadratic program and incorporates an explicit constraint on the perilune pass epoch to ensure the steered trajectory follows the reference baseline without deviating in phase. The resulting formulation has easily interpretable tuning parameters that may be obtained directly from mission requirements. The algorithm is demonstrated through Monte-Carlo simulations on the Gateway's Near Rectilinear Halo Orbit (NRHO).

Space Situational Awareness, Conjunction Analysis, and Collision Avoidance I
Room: Pine, Wednesday, August 14
10:30 AM - 12:30 PM
Session Chair(s): Kyle DeMars (Texas A&M University) and Yashica Khatri (NorthStar Earth & Space)

10:30 AM
AAS-279 : Conceptual Spaces for Collision Risk Assessment
Benjamin Reifler (The University of Texas at Austin), Anand Agrawal (University of Texas at Austin), Mitchell Rosen (Advanced Space, LLC), Brandon Jones (The University of Texas at Austin), Nathan Ré (Advanced Space)

In this paper, we propose a framework for collision risk assessment based on the theory of conceptual spaces. Conceptual spaces translate human concepts into geometry and may be used as a means of hard/soft information fusion. Our approach leverages orbital mechanics to determine one satellite's ability to reach another in a given timeframe and soft information to determine whether or not this reachability constitutes a real risk. We apply our conceptual spaces-based risk analysis to a real historical collision scenario and show that it produces an earlier warning than a traditional collision probability analysis.

10:45 AM
AAS-300 : Point processes and ergodic theory for long-term collision risk assessment from fragmentation
Emmanuel Delande (Centre National d'Études Spatiales), Christophe Taillan (Centre National d'Études Spatiales (CNES)), Marie-Anne Carpine (Département d'astrophysique - UMR AIM), Yema Paul (ISAE-SUPAERO), Vincent Ruch (CNES)

This paper presents a new solution for the efficient computation of collision risk induced by a cloud of debris stemming from a fragmented asset. Two mathematical theories are leveraged: a) a point process formulation allows for an efficient propagation of the statistics of the cloud of debris, rather than each individual piece of debris, and b) the ergodicity of close encounters between a piece of debris and a targeted asset is exploited to derive a rigorous expression of the mean number of collisions across an interval of study. The paper analyzes the parametrization and the efficiency of the new solution applied on several fragmentation events spanning across various orbital regimes.

11:00 AM
AAS-329 : Stochastic Unscented Transform: a novel approach to account for dynamic uncertainty in orbit propagation
Rachit Bhatia (West Virginia University), Piyush Mehta (West Virginia University), **Gerardo Josue Rivera Santos** (West Virginia University)

Understanding and accounting for the impact of uncertainty in atmospheric density models and their drivers is important for ensuring reliable estimation and prediction of resident space object (RSOs) trajectories in the Low Earth orbit (LEO). The recent development of probabilistic density and driver models necessitates a novel mathematical framework for effectively and efficiently characterizing the propagate the uncertainty for orbit determination and prediction. This paper presents the development of a novel stochastic unscented transform (SUT) approach that has the potential for wider applications to other domains. Results on orbit propagation and covariance, including driver and model uncertainty contributions are presented.

11:15 AM

AAS-366 : OSIRIS-REx Conjunction Screenings: Earth Gravity Assist and Earth Return Analysis and Results

Dolan Highsmith (The Aerospace Corporation), Roger Thompson (The Aerospace Corporation)

The NASA OSIRIS-REx asteroid sample return mission performed an Earth gravity assist on September 22, 2017, and returned to Earth to drop off the sample on September 24, 2023. In each case, the NASA Conjunction Assessment Risk Analysis (CARA) team screened the OSIRIS-REx trajectories against the satellite catalog in search of high-risk close approaches. This paper describes the preparation for collision avoidance and screening results, along with lessons learned, providing a baseline for support of future missions in this category, particularly as space traffic around the Earth and in cis-lunar space continues to rapidly expand.

11:30 AM

AAS-414 : Robust Collision Risk Metric for Short-Term Orbital Encounters

Yema Paul (ISAE-SUPAERO), Joan-Pau Sanchez (ISAE-Supaero)

Many orbital conjunction events lack data quality for decision-making based solely on the collision probability. This paper introduces a novel collision risk assessment metric for short-term orbital encounters, employing sensitivity analysis on the nominal relative miss distance with an extrapolation of the covariance to the time of closest approach. By modeling the orbital state estimation as a non linear stochastic system obeying to stochastic Gauss variational equations, approximating analytical solutions are derived. These solutions are used to construct the proposed risk metric, which is then evaluated on ESA's Collision Avoidance Challenge dataset, demonstrating a promising level of accuracy in forecasting collision risk.

11:45 AM

AAS-458 : Characterization of the minimum warning time for low-thrust collision avoidance maneuvers

Lamberto Dell'Elce (Inria), Frank de Veld (Inria), Jean-Baptiste Pomet (Inria)

Satellites equipped with low-thrust propulsion need to maneuver for a finite, possibly large, time to reduce the risk of collision to a safe threshold. This study offers a characterization of minimal requirements for such time. We first introduce a state vector consisting of the time of closest approach and the orbital elements of the primary at this time, and we deduce its equations of motion. Necessary conditions of optimality are then disclosed, and an approximate solution is proposed. A thorough analysis of the global optimality of this solution is proposed with special focus on the computation of cut and conjugate loci.

12:00 PM

AAS-470 : Fast Monte Carlo Conjunction Analysis using Importance Sampling and the Cross-Entropy Method

Ryan Ketzner (University of Central Florida), Tarek Elgohary (University of Central Florida)

The most commonly used tools for probability of collision (PC) assessment today rely on simplifying assumptions to make the problem tractable, resulting in a biased estimate which does not always accurately reflect the true risk. When these simplifying assumptions break down, spacecraft operators are forced to resort to brute-force Monte Carlo (BFMC) simulation to resolve the PC. We present an algorithm for Monte Carlo PC estimation using importance sampling and the cross-entropy method, called cross-entropy Monte Carlo (CEMC). CEMC gives an unbiased estimate of the PC and requires no new restrictive assumptions, while being orders-of-magnitude faster than BFMC.

Spacecraft Guidance, Navigation and Control (GNC) IV
Room: Centennial E , Wednesday, August 14
10:30 AM - 12:30 PM
Session Chair(s): Siamak Hesar () and Jason Leonard (KinetX)

10:30 AM

AAS-381 : Learning-Aided Chance-Constrained Control: Safety-Assured Control & Learning Under Spacecraft Mission Uncertainties

Pete Lealiiee (The University of Texas at Austin), Naoya Kumagai (Purdue University), Maruthi R. Akella (The University of Texas at Austin), Kenshiro Oguri (Purdue University)

Spacecraft missions planned for regions yet to be thoroughly characterized by prior missions are subject to substantial uncertainties in regional perturbations – e.g. local gravity field, solar radiation pressure, and n-body effects. Furthermore, operational uncertainties in navigation and control lend additional obstacles to ensuring spacecraft mission safety. This paper provides a framework for unifying safety-assured navigation and statistical system learning through applications of chance-constrained optimal control and Bayesian Inference. The proposed solution is compared with a conventional chance-constrained optimal control approach in a stationkeeping scenario where gravity field effects are poorly known and uncharacterized.

10:45 AM

AAS-399 : Passive Fluid Transport in Microgravity Environments for the Stabilization of Rotating Spacecraft

Martin Rosales (National Aeronautics and Space Administration), Eduardo Bidot-Lopez (National Aeronautics and Space Administration), **Matthew Wittal** (National Aeronautics and Space Administration)

Rotating spacecraft offers the potential to create artificial gravity for extended space missions. This paper examines a rotating vehicle that must maintain stability around a central point. Consequently, a durable and passive spin stabilization system is essential, requiring the passive transport of fluids. A system consisting of microcapillary bundles and hydraulic ram pumps is explored to transport fluids without added external added to the system. A model of the system validates the approach, showing that passive stabilization is possible. This model can be expanded for broader applications, including mass redistribution, a theoretical fluid ring, and 3 axis rotating systems.

11:00 AM

AAS-407 : Orbit Determination through Cosmic Microwave Background Radiation

Pedro Kukulka de Albuquerque (George Mason University), André Rossi Kuroswiski (University of Central Florida), Annie S. Wu (University of Central Florida), Willer Gomes dos Santos (Aeronautics Institute of Technology (ITA)), Paulo Costa (George Mason University)

This research focuses on the innovative use of Cosmic Microwave Background (CMB) radiation for Initial Orbit Determination (IOD). By employing CMB as a reference signal, this research presents a new method less reliant on extensive pre-existing environmental data, thus offering significant advantages for space missions unrelated to Earth-specific conditions. The study demonstrates the application of CMB to determine spacecraft velocity and position using minimal prior information, using signal processing and Artificial Intelligence (AI). Results indicate the potential of CMB-based navigation to enhance the autonomy and flexibility of spacecraft operations.

11:15 AM

AAS-432 : Exploiting Fokker-Planck-Equation For Tracking Error Control: Application to Transport In Cislunar Regime

Taritri Bhattacharjee (Penn State University), Puneet Singla (The Pennsylvania State University)

This paper utilizes the stationary solution for Fokker-Planck-Kolmogorov equation (FPKE) to design a simple feedback controller for Hamiltonian systems with non-conservative control input and Gaussian white noise disturbance term. The
FPKE provides the evolution of state probability density function (PDF) n through a nonlinear dynamical system. The existence of stationary solutions for FPKE through control input implies that all state trajectories will go to stationary PDF
and hence guarantees the asymptotic stability. The derived result is used for station keeping for a Halo orbit and nonlinear guidance for a transfer between L1 and L2 planar Lyapunov orbits.

11:30 AM

AAS-436 : Chance-Constrained Sensing-Optimal Path Planning for Safe Angles-only Autonomous Navigation

Minyoung Ra (Purdue University), Kenshiro Oguri (Purdue University)

This paper explores the optimization of navigation trajectory planning for safe spacecraft autonomy using a chance-constrained stochastic control approach. It addresses the challenge of ensuring safety in autonomous spacecraft missions by combining angles-only navigation models and robust control mechanisms. Highlighting the limitations of traditional active-sensing maneuver planning, which often neglects safety concerns, the study proposes a new cost formulation that enhances trajectory observability and meets safety constraints. Employing a chance-constrained framework suited for non-linear observation models, the paper demonstrates computational efficiency and effectiveness through numerical simulations in various dynamic environments.

11:45 AM

AAS-450 : Artemis II: Linear Covariance Analysis Using Explicit Vent Force States

Christopher DSouza (NASA/JSC), **Jack Joshi** (University of Texas at Austin), Matthew Gualdoni (NASA Johnson Space Center), David Woffinden (NASA Johnson Space Center), James McCabe (NASA Johnson Space Center), Collin York (NASA Johnson Space Center)

Traditionally, the foundation of linear covariance analysis is based upon linearizing the error dynamics about a nominal trajectory, where it is assumed that the errors are zero-mean. However, the vehicles supporting the upcoming crewed Artemis missions, beginning with Artemis II, will be subject to non-zero mean perturbations that are not accounted for in the nominal trajectory
design. This work proposes and analyzes the implementation of explicit state vent force states in a linear covariance analysis, and compares the resulting model to a process noise based approach.

12:00 PM

AAS-485 : Crater Detection in Images using Template Matching

Ava Thrasher (Georgia Institute of Technology), John Christian (Georgia Institute of Technology), Giovanni Molina (Intuitive Machines), John Pelgrift (KinetX, Inc.), Derek Nelson (KinetX, Inc.), Coralie Adam (KinetX, Inc. | AAS Board)

Optical terrain relative navigation (TRN) relies on the detection of planetary surface features which can be used to infer the position of the spacecraft. Craters are one suitable surface feature for this type of TRN. This work investigates a crater detection methodology based on template matching detection in the frequency domain. The detection of simple craters in an image is accomplished by scale invariant template matching between the image and a rendered crater template. A discussion of simple crater profile and surface modeling, computationally efficient rendering, and template matching is included along with an analysis of the detection method’s accuracy.

Orbital Dynamics, Perturbations, and Stability I
Room: Centennial E , Wednesday, August 14
2:00 PM - 3:15 PM
Session Chair(s): Oscar Fuentes-Muñoz (NASA Jet Propulsion Laboratory/Caltech) and Anubhav Gupta (In Orbit Aerospace, Inc. & University of Colorado Boulder)

2:00 PM

AAS-343 : Relative Trajectories in the Circular-Restricted N-Body Problem (CRNBP) for a Sun-Mars L4 Long-Period Orbit

Annika Gilliam (Air Force Institute of Technology), Christian West (Air Force Institute of Technology), David Curtis (Air Force Institute of Technology), Robert Bettinger (Air Force Institute of Technology, Department of Aeronautics & Astronautics)

Expanding interest into asteroids and systems further away from the traditional Earth environment necessitates an investigation into challenges that rendezvous and proximity operations (RPO) may face in this new domain. RPO trajectories in the Circular Restricted 3-Body Problem (CR3BP) for the Sun-Mars system will be compared to trajectories in the Circular Restricted N-Body Problem (CRNBP) with identical initial conditions for the Sun-Mars-Jupiter-Earth system to include additional multi-body effects. Initial results indicate that bounded relative trajectories likely do not exist in the CRNBP model, but some initial conditions that place Jupiter further from the satellite formation produce significantly more favorable conditions.

2:15 PM

AAS-346 : Benefits of Using A Variational Integrator for the Circular Restricted Full Three-Body Problem

Herman Gunter (Embry-Riddle Aeronautical University), Annika Anderson (Embry-Riddle Aeronautical University), David Canales Garcia (Embry-Riddle Aeronautical University), Morad Nazari (Embry-Riddle Aeronautical University)

Simultaneous tracking of orbit and attitude in multibody systems is essential for accurately understanding motion. The cislunar region is effectively modeled using the circular restricted full three-body problem (CRF3BP), which accurately predicts spacecraft behavior. However, numerical integration of the CRF3BP becomes computationally expensive when using typical propagation methods for its point-mass counterpart (circular restricted three-body problem). A state-of-the-art first-order variational integrator is modified to match the accuracy of a conventional ode45 while preserving geometric properties of the system. Numerical results demonstrate the benefits of using a variational integrator within a fourth-order Runge-Kutta scheme in terms of accuracy and computational costs.

2:30 PM

AAS-421 : Sensitivity Analysis of Stretching Directions for Bounded Motion along Libration Point Orbits

Isabel Nolton (Georgia Institute of Technology), Yuri Shimane (Georgia Institute of Technology), Kento Tomita (Georgia Institute of Technology), Koki Ho (Georgia Institute of Technology)

This study conducts a sensitivity analysis of stretching directions along libration point orbits (LPOs) in the circular and elliptical restricted three-body problem. Given the system's inherent dynamical complexity, understanding the linear stability of LPOs is vital for spacecraft motion and station-keeping. We define separation time as the coasting period during which an initial perturbation is contained within a specified phase space threshold. We investigate how the stretching directions and corresponding separation time change with different maximum deformation thresholds along the LPO. Furthermore, we compare these results to the system's stretching directions when employing various propagation times for unrestricted maximum deformation.

Rendezvous, Relative Motion, and Proximity Operations II
Room: Pinon, Wednesday, August 14
2:00 PM - 3:15 PM
Session Chair(s): Sofia Catalan (The University of Texas at Austin) and Christopher Roscoe (Ten One Aerospace)

2:00 PM
AAS-360 : Multiplicative Approach to Constrained Stochastic Attitude Control with Application to Rendezvous and Proximity Operations
Yuji Takubo (Stanford University), Simone D'Amico (Stanford University)

This paper introduces a 6 degrees-of-freedom (DoF) stochastic motion planning and control scheme for spacecraft rendezvous, proximity operation, and docking (RPOD) with covariance steering and passive compliance of safety constraints. The novel architecture makes rotational and translational motion planners inform each other for sequential, iterative, and asynchronous motion planning, which is suited to onboard implementation because of the difference in time scales of the two domains. This motion planning also meets the roto-translational passive safety constraint that avoids collision and unsafe spacecraft pointing in the presence of contingency. The proposed approach is deployed in high-fidelity dynamics and validated via Monte Carlo simulations.

2:15 PM
AAS-377 : Applying Correlation Methods to Relative Navigation
Rachel Mamich (University of Texas at Austin), Renato Zanetti (Blue Origin)

This study introduces an adaptive relative navigation filter, employing correlation methods to autonomously discern and estimate the impacts of unmodeled perturbations on a two spacecraft relative inertial system. These perturbations are construed as stochastic process noise. This research demonstrates that the integration of adaptive strategies empowers the filter to dynamically accommodate unforeseen perturbations, facilitating estimation without assumptions regarding timing, optimality, or magnitude. The findings underscore the versatility of correlation methods, and their ability to handle the nonlinear dual inertial system presented.

2:30 PM
AAS-392 : Multiview optical navigation for Space Manipulator Systems during In-Orbit servicing missions
Niccolò Faraco (Politecnico di Milano), Michele Maestrini (Politecnico di Milano), Mauro Massari (Politecnico di Milano), Pierluigi Di Lizia (Politecnico di Milano)

Given the high number of inactive satellite orbiting and polluting the space around the Earth, In-Orbit servicing missions will play a substantial role in the aerospace industry in the upcoming decades. Using Space Manipulator Systems (SMS) is among the most promising techniques envisioned as possible solutions to the problem. A novel approach is proposed to concurrently perform non-linear filtering on the attitude and position of both the base of the chasing spacecraft and the end-effector of the manipulator within a fully relative framework. Monocular cameras mounted directly on the chaser base and the end-effector provide the measurements, effectively creating a variable-baseline stereo camera system.

2:45 PM

AAS-398 : Relative Trajectory Design Methodologies Informed by Stretching and Restoring Directions

Lorin Nugent (Purdue University), Kathleen C. Howell (Purdue University)

Stretching and restoring directions form sets of orthonormal vector bases that can be used to describe and design relative trajectories. This investigation formulates relative states as linear combinations of these principal directions to introduce techniques for relative trajectory design in the circular restricted three-body problem. Useful properties unique to 3x3 subsets of the state transition matrix are exploited to derive methodologies for two relative motion applications. The formulation is presented from a spacecraft loitering perspective and assessed along two multi-body orbits. Modifications are introduced for application to collision avoidance to present topics of further intended investigation.

Trajectory, Mission, and Maneuver Design/Optimization IX
Room: Centennial F, Wednesday, August 14
2:00 PM - 3:15 PM
Session Chair(s): Jeff Parker (Advanced Space, LLC) and Stephen West (Space Exploration Engineering)

2:00 PM
AAS-404 : Optimizing the Earth-Mars Cycler Orbit: Particle Swarm Applied to Powered Flybys
Kyle Newlin (Embry-Riddle Aeronautical University), Davide Conte (Embry-Riddle Aeronautical University)

This paper introduces a refined approach for designing Earth-Mars cycler trajectories using particle swarm optimization (PSO). By incorporating accurate planetary ephemerides and the performance of powered flybys at each gravity assist, this paper presents innovative trajectory optimization techniques that reduce propellant requirements and address the challenges of high-speed planetary encounters. The methodology details how solutions like Lambert's problem and B-plane geometry are parameterized within a PSO framework, leading to sustainable interplanetary travel. The results demonstrate the potential for improved cycler designs and suggest practical implementation in future mission design.

2:15 PM
AAS-405 : Optimal Trajectories of Electrodynamic Tethers in the Jovian System Using Indirect Method
Abdullah Alkhenani (Purdue University), Kenshiro Oguri (Purdue University), Michael Mueterthies (Blue Wave AI Labs)

Electrodynamic tethers (EDTs) offer dual benefits of space propulsion and power generation with negligible propellant use. This study proposes an indirect trajectory optimization formulation using electrodynamic tether propulsion within Jupiter’s high-density plasma regions, including the plasmasphere and Io’s plasma torus. The formulation derives analytical optimal control laws using Pontryagin’s Principle for various control problems. These include minimizing orbital energy for spacecraft on hyperbolic trajectory to facilitate Jovian orbit capture, and minimizing time to lower apoapsis for rendezvous with Io. Findings outline feasibility thresholds for capture based on tether parameters and demonstrate a minimum-time transfer trajectory to Io.

2:30 PM
AAS-408 : Thrust Magnitude Constraints for Low-Thrust Trajectory Optimization
Bryn Fanger (University of Texas at Austin), Ryan Russell (The University of Texas at Austin)

A detailed analysis of six control constraint methods for thrust magnitude limitations is presented. The methods are the inequality Augmented Lagrangian, penalty inequality Augmented Lagrangian, Heaviside Augmented Lagrangian, penalty Heaviside Augmented Lagrangian, box and newly coined implicit method. Cartesian and spherical control frames with normalization schemes are also examined, along with techniques for avoiding singularities. The resulting twenty-seven submethods are applied to ten diverse spacecraft trajectory optimization problems with up to ten revolutions. The implicit method is the simplest to implement, does not require tuning, and demonstrates the best median performance of all the non-approximate solution methods.

2:45 PM
AAS-424 : Stochastic Differential Dynamic Programming under Coupled Control and Observation
Masahiro Fujiwara (Japan Aerospace Exploration Agency), Naoya Ozaki (ISAS, JAXA)

This study proposes a new algorithm that can deal with coupled observation and control based on stochastic differential dynamic programming. The algorithm is formulated considering the filtered dynamics where the nominal control affects the estimated error covariance. In the algorithm, the control includes a vectorized feedback gain to design the feedback policy satisfying chance constraints. Besides, the semi-analytic derivatives of the filtered dynamics are derived for computational efficiency. The numerical results show that the proposed method simultaneously optimizes the nominal and feedback controllers, which can guide the system to more observable regions.

3:00 PM
AAS-426 : Time-triggered Reduced Desensitization Formulation For Solving Optimal Control Problems
Praveen Jawaharlal Ayyanathan (Auburn University), Ehsan Taheri (Auburn University)

Fuel optimal trajectories are sensitive to variations in model parameters like the thrust produced by the propulsion system. Existing desensitization techniques desensitize for the entire flight time and produce trajectories that have less dispersions to model parameter variations and a lower final cost when compared to the sensitive trajectories. This paper introduces a time-triggered desensitization mechanism by altering the Reduced Desensitization Formulation (RDF) and its effect on the optimal trajectory is studied by considering the uncertainty in the thrust magnitude of the propulsion system. By desensitizing specific segments of the trajectory, optimality of the desensitized trajectories can be improved.

Asteroid and Interplanetary Mission Design II
Room: Pine, Wednesday, August 14
2:00 PM - 3:15 PM
Session Chair(s): Jeroen Geeraert (KinetX Inc.) and Daniel Scheeres (University of Colorado Boulder)

2:00 PM

AAS-196 : Silhouette Based Gaussian Process Batch Filtering for Simultaneous Localization and Mapping about Small Bodies

Quinn Moon (University of Texas), Brandon Jones (The University of Texas at Austin), Ryan Russell (The University of Texas at Austin), Courtney Hollenberg (NASA/CalTech Jet Propulsion Laboratory), Daniel Lubey (Jet Propulsion Laboratory, California Institute of Technology), Shyam Bhaskaran (Jet Propulsion Laboratory)

A Gaussian Process (GP) is implemented within a Batch filter to model the shape of a small body and simultaneously estimate the spacecraft's state. Silhouette based measurements are simulated to extract the visible horizon of the small body Eros. Through multiple batch iterations with a declining measurement under-weighting scheme, the GP Batch algorithm estimates the body's shape to within meters of error, while also estimating the body's orientation, the body's spin rate, and the satellite's position and velocity. The maximum-likelihood estimate provided by the GP Batch Filter are to be used in subsequent Monte Carlo analyses with an iterative filter.

2:15 PM

AAS-235 : On the exploration of the asteroid 2011 UW158

Diogo Merguizo Sanchez (The University of Oklahoma)

This study explores different orbits to investigate the stability of a spacecraft near the PHA (436724) 2011 UW158. Perturbation Maps are used to assess close direct, distant retrograde, polar, and terminator orbits, as well as to locate resonant orbits around this asteroid. The model considers the asteroid as a triaxial ellipsoid with the gravitational potential expanded in spherical harmonics up to degree and order four, as well as the perturbation from the Sun, the planets, and solar radiation pressure. The results presented in this work can be used to support future missions to 2011 UW158.

2:30 PM

AAS-472 : Powered Jupiter Gravity Assists for Shortened Transit Times to Trans-Neptunian Objects

Mitchell Pentecost (University of Tennessee, Knoxville), Canaan Anderson (University of Tennessee, Knoxville), Mills Johnson (University of Tennessee, Knoxville), Noah Nash (University of Tennessee, Knoxville), Joseph Syracuse (University of Tennessee, Knoxville), Laura Von Bargen (University of Tennessee, Knoxville)

Many scientific communities are interested in the study of trans-Neptunian Objects (TNOs) due to their possible insight into the formation of the Solar System. This project investigates trajectories to three TNOs: Sedna, Makemake, and Orcus. The goal is to provide plausible flyby trajectories to these three dwarf planets that utilize a powered Jupiter gravity assist (PJGA) to decrease transit time while maintaining a reasonable payload mass upon arrival. Mission Analysis Environment (MAnE) is used to evaluate and optimize trajectories based on various parameters. Transit times of 9-20 years are considered with departure dates ranging from early 2030s to late 2050s.

2:45 PM

AAS-296 : Accurate Approach Method Using Multiple Satellites in Asteroid Flyby Exploration

Masaki Tsutsui (The University of Tokyo), Yosuke Kawabata (The University of Tokyo), Ryu Funase (The University of Tokyo), Shinichi Nakasuka (The University of Tokyo)

Performing accurate flybys of asteroids while conserving fuel is challenging due to their inaccurate positions and high relative velocities with the satellite. To address this issue, we propose a method that utilizes two satellites. The sub-satellite performs a flyby of the asteroid before the main-satellite, and its observation data is used to correct the orbit of the main-satellite. This method was evaluated based on the Delta-V and flyby accuracy. The results indicate that this method is superior to the conventional method that uses only one satellite. Additionally, we show how the inter-satellite distance and TCM timing affect the flyby.

Machine Learning and Artificial Intelligence Applied to Spaceflight, Space Autonomy I
Room: Centennial E , Wednesday, August 14
3:45 PM - 5:00 PM
Session Chair(s): Natasha Bosanac (University of Colorado, Boulder)

3:45 PM
AAS-195 : Autonomous operation of planetary geodesy mission using deep reinforcement learning
Kwonhee Lee (Georgia Institute of Technology), Brian Gunter (Georgia Institute of Technology)

Planetary geodesy missions to the Ocean worlds in the outer solar system, such as Europa, Titan, and Enceladus are essential due to their potential of harboring life. However, these missions are challenging due to the vast distance from Earth, necessitating autonomous operations for efficiency. To address this, a deep learning reinforcement learning framework tailored specifically for enabling autonomous operation of a planetary geodesy mission is presented.

4:00 PM
AAS-409 : Satellite Reorientation Using Reinforcement Learning Under Unknown Attitude Failure: Reaction Wheel and Earth-Searching Implementation
Matthew Willoughby (Embry-Riddle Aeronautical University), Hao Peng (Embry-Riddle Aeronautical University)

Previously, the authors demonstrated that when a satellite has lost communication due to unknown attitude failures, it is possible to use reinforcement learning (RL) to allow the satellite to learn to reorient its antenna towards the Earth using external torques. In this further study, internal control torques provided by reaction wheels are explored independently, and in conjuction with external control torques. In both cases the true Earth-direction is unknown, and the RL agent must learn its direction. Various attitude control and attitude determination failure modes will be considered, ensuring the RL agent can reestablish communication in every case.

4:15 PM
AAS-445 : Fine-Tuned Language Models as Space Systems Controllers
Enrico Zucchelli (Massachusetts Institute of Technology), Di Wu (MIT), Julia Briden (MIT), Christian Hofmann (Massachusetts Institute of Technology), Victor Rodriguez-Fernandez (Universidad Politécnica de Madrid (UPM)), Richard Linares (Massachusetts Institute of Technology)

Language models are complex functions capable of generating language. Thanks to the intricacy of their architectures and to the large amount of data used in their pre-training phase, they can display features thart resemble reasoning, which in turn can be exploited when utilizing them to solve control problems. This work presents a fine-tuning approach for space systems controls, in which pre-trained large language models are tuned with new data to solve control problems. Thanks to the information already contained in the models, less data than for traditional artificial intelligence approaches is required.

Rendezvous, Relative Motion, and Proximity Operations III
Room: Pinon, Wednesday, August 14
3:45 PM - 5:00 PM
Session Chair(s): Erika Limon (Blue Origin) and Paul Thompson (Blue Origin)

3:45 PM
AAS-439 : Autonomous RPOD for Arbitrarily Configured Spacecraft with Anomaly Detection
Matthew Wittal (National Aeronautics and Space Administration), Benjamin Asher (Aegis Aerospace), Morad Nazari (Embry-Riddle Aeronautical University)

Autonomous GN\&C is a necessary component for a sustainable deep-space logistics architecture. The challenges to establish robust autonomy are numerous, ranging from state uncertainty to anomaly detection and recovery. In this work, previous work investigating autonomous GN\&C for arbitrary thruster configurations and mass properties is expanded to include state uncertainty and anomaly detection. Logistics vehicles with off-center-of-mass thruster configurations and in the presence of large but realistic state uncertainties are simulated in a rendezvous, proximity operations and docking scenario. Furthermore, stuck and nonfunctional thrusters are simulated, demonstrating the vehicle's ability to identify and overcome thruster anomalies.

4:00 PM
AAS-449 : Quadratic Models for Keplerian Relative Motion
Claudio Bombardelli (Technical University of Madrid (UPM)), Alicia Martínez-Cacho (Universidad Politécnica de Madrid), **Ryan Russell** (The University of Texas at Austin)

Second-order analytical solutions for the Keplerian relative motion problem with arbitrary eccentricity are obtained as a generalization of the well-known Yamanaka-Ankersen state transition matrix (Y-A STM). The first solution results from a second-order synchronization of the recently proposed D matrix STM thereby converting time as an independent variable and making the formulation applicable to proximity operations. Interestingly, the first-order synchronization allows one to retrieve the exact Y-A STM following a completely different derivation process. Finally, another quadratic relative motion solution is developed from the universal variable formulation in cartesian coordinates. Both solutions are shown to considerably improve the accuracy of the classical Y-A STM.

4:15 PM
AAS-457 : Spacecraft Relative Motion Around SPICE Ephemeris Trajectories
David Cunningham (Space Trajectory Computation Lab, University of Texas), Ryan Russell (The University of Texas at Austin)

This work elaborates a method for propagating trajectories relative to a reference trajectory defined by an arbitrary SPICE kernel.
The model, intended for use in heavily perturbed environments, uses state transition tensors to achieve second order relative motion accuracy at the cost of a modest memory footprint. The relative dynamics are arbitrary in the context of n-body gravitational perturbations and spherical harmonics. The method has a generation stage that integrates the tensors via dense numerical integration and a propagation stage that computes relative trajectories using the interpolated tensors. Use cases with both simulated and flight data trajectories are provided.

4:30 PM

AAS-494 : Spacecraft Thruster Plume Modeling for Inter-Spacecraft Impacts

Scott Piggott (Atomos Space), Hanspeter Schaub (University of Colorado), Thibaud Teil (Laboratory of Atmospheric Space Physics, CU Boulder), Jennifer Wood (University of Colorado)

Strategic use of plume impingement on a remote vehicle will open up new types of relative spacecraft dynamics and control. This paper presents a simplified model for determining inter-spacecraft thruster plume interactions and explores the dynamical perturbations that result from these effects. A model for this type of thruster plume interacting with flat plates is presented with perturbation results computed for different vehicle geometries and then a numerical extension to this system that demonstrates the ability to use range rendering from a visualization tool. Using this model, it will be possible to explore the range of perturbations that impact spacecraft.

Trajectory, Mission, and Maneuver Design/Optimization X
Room: Centennial F, Wednesday, August 14
3:45 PM - 5:00 PM
Session Chair(s): Vishala Arya (Jet Propulsion Laboratory) and Donald Ellison (NASA Goddard Space Flight Center)

3:45 PM

AAS-456 : End-to-End Lyapunov-Based Eclipse-Feasible Low-Thrust Transfer Trajectories to NRHO

Nicholas Nurre (Auburn University), Ehsan Taheri (Auburn University)

Generating low-thrust transfer trajectories between Earth and the Near Rectilinear Halo Orbit (NRHO) selected for NASA's Gateway can be challenging due to the low control authority available from the propulsion system and the important operational constraint that the duration of all eclipses be less than a prescribed 90-minute threshold. We present a method for generating eclipse-feasible, minimum-time solutions to the aforementioned trajectory design problem using a Lyapunov control law. Particle swarm optimization is used to optimize the NRHO insertion date, time of flight, and control law parameters according to a cost function that includes a soft-penalization of eclipses. Trajectories can serve as initial guesses for high-fidelity trajectory design tools such.

4:00 PM

AAS-461 : Invariant Manifolds Representation in Three-Body Systems based on Tensor Function Approximators

Zhi Xu (Purdue University), Roha Gul (Purdue University), Mitchell Dominguez (Purdue University), Ran Dai (Purdue University), Kathleen C. Howell (Purdue University)

Invariant manifolds of periodic orbits are being leveraged to aid in trajectory design in the Circular Restricted Three-Body Problem (CR3BP). However, the intrinsic high dimensionality and the need of large-scale data points pose storage and computational burden for the calculation of these invariant manifolds. By introducing an approximation method based on tensor decomposition, we reduced the complexity for fitting polynomial-based multivariate functions. With proposed tensor function approximators, the manifolds can be efficiently and accurately represented as functions of position and velocity. Leveraging the tensor representation, an optimization framework is proposed for optimal transfer design between Libration Point Orbits (LPOs). A series of simulations are conducted to evaluate the proposed methods

4:15 PM

AAS-465 : Expanding the Class of Quadratic Control-Lyapunov Functions for Low-Thrust Trajectory Optimization

Nicholas Nurre (Auburn University), Saeid Tafazzol (Auburn University), Ehsan Taheri (Auburn University)

Control laws derived from Control-Lyapunov Functions (CLFs) offer an efficient way to find near-optimal low-thrust trajectories. An efficient and commonly used approach to construct CLFs is to consider the family of quadratic functions with (perfect) square terms only, i.e., a diagonal parameter matrix. In this paper, we explore the advantages of enlarging this family of quadratic functions by considering cross-product terms in the CLF, resulting in a full positive-definite parameter matrix. Solutions are compared to the implementation with a diagonal parameter matrix. Results show that a significant improvement in optimality is possible.

4:30 PM

AAS-480 : Optimal Control with Lyapunov Stability Guarantees for Space Applications

FNU Abhijeet (Texas A&M University), Mohamed Naveed Gul Mohamed (Texas A and M University), Aayushman Sharma (Texas A&M University), Suman Chakravorty (Texas A&M University)

This paper considers the infinite horizon optimal control problem for nonlinear space applications. Under some mild assumptions on the controllability of the system, we establish an approximate regularized solution approach consisting of a ``finite free final time" optimal transfer problem to the terminal set and an infinite horizon linear regulation problem within the terminal set, that is, shown to render the origin globally asymptotically stable. Further, we show that the approximations converge to the true optimal cost function as the size of the terminal set decreases to zero. The approach is empirically evaluated on the soft-landing space application.

Asteroid and Interplanetary Mission Design III
Room: Pine, Wednesday, August 14
3:45 PM - 5:00 PM
Session Chair(s): Angela Bowes (NASA LaRC) and Jeff Parker (Advanced Space, LLC)

3:45 PM
AAS-150 : On the Preliminary Design of Missed-Thrust Resilient Transfers for the Emirates Mission to the Asteroid Belt (EMA)
Paul Imler (Advanced Space, LLC), Jeff Parker (Advanced Space, LLC), Jeremy Knittel (LASP, University of Colorado), Fatema Al Hameli (UAE Space Agency), Mohamed Almashjari (UAE Space Agency)

This work outlines the effort of designing missed-thrust resilient transfers for the Emirates Mission to the Asteroid Belt (EMA). The spacecraft, the MBR explorer, will utilize solar-electric propulsion (SEP) and planetary gravity assists to fly by 6 main-belt asteroids and rendezvous with a seventh, 269 Justitia. Due to the ambitious mission design and use of SEP, the spacecraft will be required to thrust for extended periods of time. This requires and understanding of and resiliency to missed-thrust events. This work describes the methods used to increase the robustness of the preliminary mission design to missed-thrust events.

4:00 PM
AAS-265 : Investigating the Fusion of Mascon and Neural Network Gravity Models
Julio C. Sanchez (Universidad de Sevilla), John Martin (University of Maryland)

This paper addresses the asteroid gravity modeling problem, which poses significant challenges due to the irregular shapes and varying density distributions of these celestial bodies. This study proposes a novel approach by fusing mascon models with neural networks models. The key idea involves using a pre-trained mascon model as the foundation of the joint model. Subsequently, a neural network is fused to the previous model and trained to enhance gravity accuracy, particularly in regions where the mascon model exhibits limitations.

4:15 PM
AAS-269 : Proximity Operations Strategy for the Emirates Mission to Explore the Asteroid Belt (EMA)
Jeff Parker (Advanced Space, LLC), Fatema Al Hameli (UAE Space Agency), Jeremy Knittel (LASP, University of Colorado), Sandeep Baskar (Advanced Space LLC), Paul Imler (Advanced Space, LLC), Mohamed Almashjari (UAE Space Agency)

The Emirates Mission to Explore the Asteroid Belt (EMA) will investigate seven or more asteroids in the main belt, including a campaign to rendezvous with and orbit the asteroid 269 Justitia. This asteroid is one of the reddest objects in the main belt and has an expected diameter between 50 and 54 kilometers. The asteroid's high mass requires careful expenditure of fuel to efficiently explore the body. This paper describes the phases of the proximity operations campaign, with objectives that include mapping the gravity field and physical properties of the body and deploying a lander to Justitia's surface.

4:30 PM

AAS-280 : Preliminary Mission Determination for Asteroid (29075) 1950DA

Evan Blosser (University of Oklahoma), Diogo Merguizo Sanchez (The University of Oklahoma)

This work focuses on the discovery of periodic orbits around the asteroid (29075) 1950DA.Utilizing Mass Concentration (MASCON) models of 1950DA, with the Poincaré surface of sections, the 3-body problem is expanded to an N-body problem centered inside the point cloud defining the models. From Poincaré sections, orbits can be determined for future missions
regarding the asteroid. The discovery of possible resonance orbits would allow us to leverage a spacecraft by creating a binary system with the spacecraft and 1950DA. The success of this could divert 1950DA from its current course, eliminating its risk as a potentially hazardous asteroid (PHA).

4:45 PM

AAS-289 : Unlocking Asteroid Potential: Utilizing Low-Energy, Weak Stability Boundary Trajectories for Asteroid Redirection

Peter Schmitt (Embry-Riddle Aeronautical University), Kenya Ruiz (Embry-Riddle Aeronautical University), Davide Conte (Embry-Riddle Aeronautical University)

Over 34,000 near-Earth asteroids have been discovered orbiting the Sun. Many present potential opportunities for research, exploration, and in-space mining missions. We explored asteroid candidates, with future Earth close encounters, based on
MOID (< 0.05 AU), v_∞ (< 10 km/s), estimated diameter (< 50 m), encounter time (2030-2099), and calculated redirect Δv, suitable for redirection from solar orbits into the Earth-Moon system using WSB trajectories. Based on previous WSB missions such as CAPSTONE and SLIM, we determined the required entry position and velocity for the WSB. TBD asteroids were found suitable for this maneuver.

Asteroid and Interplanetary Mission Design IV
Room: Centennial F, Thursday, August 15
8:30 AM - 10:00 AM
Session Chair(s): Powtawche Valerino (NASA Marshall Space Flight Center)

8:30 AM
AAS-347 : Preliminary Assessment of Multi-Impactor Strategy for Planetary Defense
Victoria Rozek (University of Oklahoma), Diogo Merguizo Sanchez (The University of Oklahoma)

A potentially hazardous asteroid (PHA) is a near-Earth object whose close passage to Earth has a non-zero collision risk. One of the strategies considered for mitigating this risk is the kinetic impactor, successfully demonstrated in the past. This work assesses the feasibility and implementation of a technique that uses several sequential small kinetic impactors applied to change the PHA's orbit as an analog to continuous thrust propulsion. In the analysis, the change in the asteroid's orbital radius is calculated as a function of the number of impactors, the time between impacts, and the total time.

8:45 AM
AAS-373 : Shape Model-Independent Autonomous Asteroid Navigation: Analysis on Observability and Feasibility
Aaron Liao (Purdue University), Kenshiro Oguri (Purdue University)

This paper presents an autonomous multi-satellite navigation architecture for asteroid exploration, without relying on asteroid shape model information. Asteroid exploration missions deal with significant challenges due to uncertainties associated with the dynamical environment surrounding asteroids and communication time latencies. The proposed architecture leverages the perturbed environment around asteroids and multiple satellites to improve navigation accuracy. The perturbed environment is also used to design non-Keplerian orbits including terminator and resonant terminator orbits, which are useful for their stability properties and geometric diversity for global mapping. Additionally, we conduct an observability analysis along these trajectories using the observability Gramian.

9:00 AM
AAS-441 : On the Design and Results of Preliminary Monte Carlo Analysis for the Emirates Mission to the Asteroid Belt
Sai Chikine (Advanced Space), Paul Imler (Advanced Space, LLC), Andrew Koehler (Advanced Space), Michael Caudill (Advanced Space, LLC), Jeff Parker (Advanced Space, LLC), Jeremy Knittel (Laboratory for Atmospheric and Space Physics (LASP)), Mohamed Almashjari (UAE Space Agency), Amanda Herring (Advanced Space, LLC)

The Emirates Mission to the Asteroid Belt (EMA), launching in 2028, is an ambitious mission to rendezvous with a main belt asteroid --- 269 Justitia --- while flying very close by 6 other asteroids, all using a low thrust solar electric propulsion (SEP) system. These low thrust levels require very long thrust arcs, which poses challenges for all areas of mission design, including for Monte Carlo analysis, compared to chemical maneuver designs. This work describes the Monte Carlo modeling approach as well as analysis results in the presence of dynamical errors, navigation uncertainty, and maneuver execution errors.

9:15 AM

AAS-451 : Point Cloud-based Optical Navigation for EMA Proximity Operations at Asteroid Justitia

Jacopo Villa (Laboratory for Atmospheric and Space Physics), Jeremy Knittel (Laboratory for Atmospheric and Space Physics (LASP)), Jay McMahon (CCAR (Colorado Center for Astrodynamics Research))

We present the optical navigation strategy devised for proximity operations at asteroid Justitia, to be visited by EMA in 2034. The proposed approach is a novel terrain-relative navigation paradigm. Traditional landmark-based navigation at small bodies demands complex operational procedures, such as reconstructing a landmark catalog and a high-resolution shape model. We propose using a landmark-free algorithm based on visual point clouds, named CloudNav. The camera pose is estimated by registering two whole sets of temporary surface points, triangulated from consecutive images. We show navigation performance and present the operational strategy chosen to support the proposed technique, and vice versa.

9:30 AM

AAS-467 : Rapid Mission Design Pipeline to Enable Cislunar Rideshares for Deep Space Missions

Demyan Lantukh (AstroForge), Colin Helms (AstroForge)

The advent of many potential lunar missions motivates methods to leverage those flights as potential ride-share opportunities for low-cost access to deep space. However, these cislunar missions have large variability in departure asymptote and secondary missions lack of control over launch date. As a result, a mission design pipeline has been developed and demonstrated to speed up the process of designing a deep space mission. This pipeline approach allows planning and re-planning of missions to Near Earth asteroids quickly enough to keep up with the changing conditions of a cislunar rideshare opportunity.

Machine Learning and Artificial Intelligence Applied to Spaceflight, Space Autonomy II
Room: Centennial E , Thursday, August 15
8:30 AM - 10:00 AM
Session Chair(s): Shota Takahashi (Kayhan Space Corp)

8:30 AM

AAS-121 : On Dynamic Mode Decomposition for Nonlinear Periodic Systems with a Focus on Orbital Mechanics

Sriram Narayanan (The Ohio State University), Mohamed Naveed Gul Mohamed (Texas A and M University), Indranil Nayak (Ohio State University), Suman Chakravorty (Texas A&M University), Mrinal Kumar (The Ohio State University)

This paper discusses the predictive capabilities of Dynamic Mode Decomposition (DMD) for orbital mechanics, with a focus on the Hankel variant of DMD applied to geocentric orbits. This variant leverages a stacked series of time-delayed observations for system characterization and subsequent prediction. The paper presents a theoretical framework outlining the minimum number of time delays for precise reconstruction of periodic trajectories, verified through empirical investigation. Further, it outlines optimal training window sizes and corresponding prediction capabilities. The importance of these training parameters for DMD is highlighted through a comparative analysis of its performance on two satellite examples: the ISS and MOLNIYA-3-50 including the different perturbations in orbit.

8:45 AM

AAS-151 : Diffusion Models For Generating Ballistic Spacecraft Trajectories

Tyler Presser (University of Southern California), Agnimitra Dasgupta (University of Southern California), Daniel Erwin (University of Southern California), Assad Oberai (University of Southern California)

Diffusion Models, a type of generative model that iteratively learns to denoise data, have shown state-of-the-art results in multivariate time series forecasting and robotic trajectory planning. Using diffusion models, this work implements a novel generative framework to produce ballistic transfers from Earth to Mars. We analyze the model's ability to learn the characteristics of the original dataset and its ability to produce transfers that follow the underlying dynamics. Ablation studies assess performance variation with model size and trajectory resolution, and we design a performance benchmark to assess trajectory design usefulness. Results showcase useful properties of diffusion models for trajectory design systems.

9:00 AM

AAS-208 : Reinforcement Learning for satellite autonomy under different cloud coverage probability observations

Lorenzzo Mantovani (University of Colorado, Boulder), Yumeka Nagano (University of Colorado, Boulder), Hanspeter Schaub (University of Colorado)

The paper explores the use of Deep Reinforcement Learning (DRL) for Agile Earth Observing Satellite scheduling problem, considering cloud coverage uncertainty. Clouds affect the ability of satellites to image ground targets, degrading the system’s performance. Policies obtained using DRL can solve the satellite scheduling problem while accounting for changing information, such as cloud coverage. Hence, this study investigates agents’ performance with varying levels of cloud coverage information. Results suggest that agents trained with cloud coverage data outperform those without; the agent trained in an environment with cloud uncertainty models outperforms the agent trained without it, even without observing cloud probabilities.

9:15 AM

AAS-224 : An unsupervised physics-informed neural network for finding optimal low-thrust transfer trajectories with the direct method

Thomas Goldman (Royal Netherlands Aerospace Centre (NLR)), Kevin Cowan (Delft University of Technology)

This work proposes an unsupervised Physics-Informed Neural Network (PINN) for solving optimal control problems with the direct method to design and optimize transfer trajectories. The network adheres analytically to boundary conditions and includes the objective fitness as regularization in its loss function. A test scenario of a planar Earth-Mars low-thrust optimal-fuel transfer and rendezvous is used to demonstate that the PINN effectively identifies near-optimal solutions across a wide range of initial and final constraints. The PINN shows promise as a preliminary design tool for trajectory optimization in challenging dynamical conditions.

9:30 AM

AAS-498 : Multi-Objective Lunar Landing Mission Design Using Neural ODEs with Reservoir Computing Architecture for Trajectory Control Laws

Satoshi Ueda (Japan Aerospace Exploration Agency), Hideaki Ogawa (Kyushu University)

This paper proposes a new methodology that applies a reservoir computing architecture to spacecraft trajectory control laws. The proposed methodology is an extension of the control law using neural ordinary differential equations (ODEs). The control laws using neural ODEs offer various advantages over conventional control methodologies, including development of robust control laws that can achieve the objective in any state without relying on a reference trajectory. The application of reservoir computing enables global search through evolutionary computation in addition to gradient-based optimization of learning parameters, extending the application beyond control laws to multi-objective mission design optimization.

Orbital Dynamics, Perturbations, and Stability II
Room: Pine, Thursday, August 15
8:30 AM - 10:00 AM
Session Chair(s): Benjamin Sunderland (Kayhan Space) and Paul Thompson (Blue Origin)

8:30 AM

AAS-103 : Four Body Invariant Structures and Chaos Analysis for Jovian Multi-Moon Ballistic Transfers

Suryansh Aryan (Virginia Tech), Riley Fitzgerald (Virginia Tech)

A ballistic capture is a highly-efficient low-energy transfer method requiring practically no fuel consumption. A topic of research in the Circular Restricted Three Body Problem (CRTBP) central to such transfers is the feasibility of ballistic transfer tubes emanating from the unstable quasi-periodic orbits around libration points. Our study searches for invariant quasi-periodic tori around libration points in the Planar Concentric Circular Restricted Four Body Problem (PCCFBP), where a third primary perturbs the non-integrable system. A family of such quasi-periodic invariant tori are computed for the Jupiter-Europa-Ganymede and Jupiter-Callisto-Ganymede system, and we assess the existence of invariant heteroclinic connections in PCCFBP.

8:45 AM

AAS-134 : On Solar Radiation Pressure: Influence of Area-to-Mass Ratio Uncertainty and Various Shadow Models

Mark Wolf (The Ohio State University), Rondale Balo (The Ohio State University), Sriram Narayanan (The Ohio State University), Mrinal Kumar (The Ohio State University)

High-fidelity orbit forecasting of space assets is imperative given the rapid increase in activity in every orbital regime over the past several years. To advance this objective, various aspects of solar radiation pressure perturbation have been investigated using numerical techniques to determine the feasibility of estimating the area-to-mass ratio of a satellite and studying different shadow region models. In this work, an adaptive Monte Carlo approach is used for forecasting under uncertainty, in combination with an outer parameter estimation loop. Cylindrical and conical shadow region models are compared to understand the impact of different shadow models on SRP perturbation propagation.

9:00 AM

AAS-209 : Manifold Driven Continuous-Thrust Transfers between L1 and L2 Periodic Orbits in Cis-lunar Space

Kevin Alvarado (Rensselaer Polytechnic Institute), Sandeep Singh (Rensselaer Polytechnic Institute)

Spacecraft catering to “permanent" stations in the lunar vicinity will require frequent travel between periodic orbits around the Earth-Moon L1 and L2 Lagrange Points. Depending on the mission requirements and available fuel, transfer architectures must be studied and trade-offs between flight time and fuel consumption quantified. Asymptotic flow near periodic orbits within the CR3BP could be leveraged for densification of the solution space. This paper presents a manifold-driven, continuous-thrust architecture based on asymptotic initial and terminal coast segments. Interesting insights regarding the linear correlation between fuel costs and change in osculating elements associated with the initial-terminal conditions are provided.

9:15 AM

AAS-234 : Fully Coherent Model of Dynamics Around Binary Asteroids: Application to Didymos and the DART Impact

Alex Meyer (University of Colorado Boulder), Daniel Scheeres (University of Colorado Boulder)

The dynamical environment around binary asteroids has been studied in depth, but these models typically make assumptions about the eccentricity or rotational stability of the asteroids. In this work we develop a fully coherent dynamical model accounting for the gravitational influence of two arbitrarily shaped asteroids and the Sun, allowing for eccentricity and irregular spin states. We apply this model to Didymos after the DART impact to determine the stability of orbits in the perturbed system. We then study the behavior of ejecta and identify regions in which ejecta may be long lived, a concern for the Hera mission.

Rendezvous, Relative Motion, and Proximity Operations IV
Room: Pinon, Thursday, August 15
8:30 AM - 10:00 AM
Session Chair(s): Erika Limon (Blue Origin) and Simone Servadio (Iowa State University)

8:30 AM
AAS-127 : On Spacecraft Superelliptical Relative Motion
Tristan Griffith (AFRL/RVSV), Alex Sizemore (AFRL/RVSV), Joseph Kloeppel (BlueHalo)

Due to the dominant physics associated with orbital dynamics, it is often desirable to follow emergent, natural motion trajectories as a means of minimizing fuel use on-orbit. For example, during spacecraft rendezvous and proximity operations, the inherent dynamics can be used to circumnavigate a resident space object. Natural motion circumnavigation is elliptical in geometry and is viewed as a safe, efficient maneuver in operations. Here, the mathematical framework for superelliptical circumnavigation is presented. It will be shown that by making slight modifications to natural motion trajectories, this framework provides more flexibility in trajectory design without imposing significant fuel costs.

8:45 AM
AAS-132 : Relative Controllable and Reachable Set Computation Methods for Low-Thrust Trajectories
Robyn Natherson (University of Colorado, Boulder), Daniel Scheeres (University of Colorado Boulder)

The controllable set characterizes the initial conditions of a system, which delineate an envelope in which a spacecraft must reside to be able to reach a target. Controllable and reachable sets are of interest for relative motion scenarios and as a framework to study the robustness of trajectories to unplanned outages. This work presents three methods for the computation of the controllable set including constraints for directional solutions. Classical optimal control techniques are applied to a maximum state problem solved backwards in time. The characteristics of each solution method are explored through examples which demonstrate the utility of these sets.

9:00 AM
AAS-172 : Fast, Near-Optimal Trajectory Design for Low-Thrust Spacecraft Rendezvous using Linear Quadratic Control Methods
Rutvik Marathe (Starfish Space)

A new technique for on-orbit trajectory control has been developed for low-thrust spacecraft rendezvous missions. In this paper, a Linear Quadratic Regulator (LQR) controller is formulated and filtered to determine the optimal feedback control law for low-thrust spacecraft rendezvous. The controller is used to demonstrate fast rendezvous trajectories in multiple regimes. Linear Quadratic Integral and Linear Quadratic Gaussian control methods are then developed in order to enable effective rendezvous under the presence of both orbital perturbations and measurement noise. The LQI and LQG control formulations are demonstrated in a Low-Earth Orbit (LEO) mission with orbital perturbations and measurement noise modeled.

9:15 AM

AAS-173 : Spacecraft rendezvous and proximity operation control in the Cislunar region

Seur Gi Jo (Embry-Riddle Aeronautical University), Vikas Patel (Embry-Riddle Aeronautical University), Dongeun Seo (Embry-Riddle Aeronautical University), David Canales Garcia (Embry-Riddle Aeronautical University)

This paper proposes a method of translational and rotational control for rendezvous and proximity operations (RPO) in the Cislunar realm. The translational motion in the Cislunar realm is described as a non-linear system. For a successful RPO mission, a controller needs to guarantee stability in the non-linear regime. Additionally, in the case of the rotational motion, the controller shall operate in uncertain environments. Thus, a Lyapunov based control is proposed to provide stable translational motion, and an adaptive control for rotational motion. The RPO is successfully achieved with these in circumstances when the moment of inertia is not precisely known.

9:30 AM

AAS-176 : Structural Controllability Analysis for Linear Dynamics with Relative Orbit Elements

TAKAHIRO SASAKI (Japan Aerospace Exploration Agency)

This paper develops the linear dynamics with ROEs considering the orbital perturbations. Then, structural controllability of the linear dynamics is considered using the graph theory. Based on the structural controllability analysis, new linear dynamics with ROEs has been developed, considering its controllability. Through the numerical examples, the effectiveness and improvements of controllability in the proposed dynamics have been demonstrated.This paper develops the linear dynamics with ROEs considering the orbital perturbations. Then, structural controllability of the linear dynamics is considered using the graph theory. Based on the structural controllability analysis, new linear dynamics with ROEs has been developed, considering its controllability. Through the numerical examples, the effectiveness and improvements of controllability

9:45 AM

AAS-197 : Event Data Processing and Filtering for Far-Field Spacecraft Rendezvous

Sofia Catalan (The University of Texas at Austin), Brandon Jones (The University of Texas at Austin), Michael Shoemaker (NASA GSFC)

While the flight heritage of frame-based cameras results in their continued use for spacecraft, event-based cameras have promising advantages for on-orbit use. With improvements in dynamic range capabilities and high return rates, event cameras can continue to provide data in lighting conditions where traditional cameras struggle. This paper uses simulated events and range measurements to estimate relative spacecraft position and velocity in far-field rendezvous scenarios. The integrated softare pipeline described in this work compares different filtering methods with single and multiple target tracking cases to estimate translational states between the observing camera and target spacecraft.

Machine Learning and Artificial Intelligence Applied to Spaceflight, Space Autonomy III
Room: Centennial E , Thursday, August 15
10:30 AM - 12:30 PM
Session Chair(s): Shota Takahashi (Kayhan Space Corp)

10:30 AM
AAS-284 : Machine Learning Application For Lambert's Problem
Sungmoon Choi (Iowa State University), Ossama Abdelkhalik (Iowa State University), Ashwati Das-Stuart (Purdue University), Rodney L. Anderson (Jet Propulsion Laboratory/Caltech)

This study presents a neural network Lambert's approximator, a novel approach to address Lambert's problem using deep learning. The main contribution lies in providing a means to approximate transfer trajectories for preliminary mission design, utilizing machine learning in conjunction with prior knowledge in astrodynamics. By normalizing the gravitational parameter of a central body and initial distance, this approach is applicable to any two-body system. The proposed neural network model, trained on a dataset of transfer trajectories, demonstrates efficiency in approximating these trajectories. The study delves into the neural network architecture, training methodology, and performance evaluation, highlighting the potential of this approach to enhance the efficiency of preliminary mission design process.

11:15 AM
AAS-378 : Markers Identification for Relative Pose Estimation of an Uncooperative Target
Batu Candan (Iowa State University), Simone Servadio (Iowa State University)

This paper introduces a novel method using chaser spacecraft image processing and Convolutional Neural Networks to detect structural markers on the European Space Agency's (ESA) Environmental Satellite (ENVISAT) for safe de-orbiting.
Advanced image pre-processing techniques, including noise addition and blurring are employed to improve marker detection accuracy and robustness. Initial results show promising potential for autonomous space debris removal, supporting proactive strategies for space sustainability. The effectiveness of our approach suggests that our method could significantly enhance the safety and efficiency of debris removal operations by implementing more robust and autonomous systems in actual space missions.

11:30 AM
AAS-384 : AI-assisted detection and tracking of particles orbiting around small bodies
Aurel Zeqaj (University of Bologna), Marco Zannoni (University of Bologna), Paolo Tortora (Alma Mater Studiorum - Università di Bologna), Ryan Park (Jet Propulsion Laboratory)

We present an AI-based pipeline for the detection and tracking of small (centimeter-scale) particles orbiting around small bodies. The pipeline runs through three main steps: first, synthetic images representing the particles' orbits are generated using a 3D computer graphics software. Then, a Convolutional Neural Network, trained on synthetic images, is used to detect the particles on real data and extract their positions. Finally, their trajectories are reconstructed by exploiting different techniques (AI and classical orbit determination based). The final goal is to integrate the obtained trajectories in an orbit determination software to improve the gravity field of the small body.

11:45 AM

AAS-391 : Adaptive Mars Entry Guidance with Atmospheric Density Estimation

Felipe Giraldo-Grueso (The University of Texas at Austin), Andrey Popov (The University of Texas at Austin), Renato Zanetti (Blue Origin)

Considerable variability of atmospheric density on Mars poses challenges for traditional numerical predictor-corrector methods, especially in uncertain environments where precise control of the vehicle's bank angle is crucial. This work addresses these challenges by introducing a new adaptive guidance algorithm based on a recently proposed navigation solution. The navigation solution, originally designed in an open-loop fashion, estimates atmospheric density by utilizing an online-adapting neural network to correct for discrepancies with the true atmospheric density. The guidance algorithm uses this neural network, coupled with a simple exponential model, to propagate the current state to a final target location in the prediction step of the Fully Numerical Predictor-Corrector Entry Guidance (FNPEG) framework.

12:00 PM

AAS-403 : Orbital Maneuver and Interplanetary Trajectory Design Via Reinforcement Learning

Roberto Cuéllar (Embry-Riddle Aeronautical University), Daniel Posada (Embry-Riddle Aeronautical University), Troy Henderson (Embry-Riddle Aeronautical University), Reza Karimi (NASA-JPL)

This paper explores the application of reinforcement learning (RL) in designing continuous low-thrust orbital maneuvers and an interplanetary mission to rendezvous with the asteroid Apophis. RL outperforms optimal control methods in adapting to unknown disturbances, crucial for missions with evolving dynamics. Formulating the problem using modified equinoctial elements, RL, particularly Proximal Policy Optimization (PPO), proves effective in handling complex, continuous control tasks without compromising fidelity. The spacecraft's trajectory design is modeled as a Markov Decision Process, optimizing rewards through various reward functions. Validation against deterministic optimal control solutions ensures RL efficacy for such missions.

Orbital Debris and Space Environment II
Room: Pinon, Thursday, August 15
10:30 AM - 12:30 PM
Session Chair(s): Brandon Jones (The University of Texas at Austin) and Smriti Nandan Paul (Missouri University of Science and Technology)

10:30 AM

AAS-325 : An Evolutionary Game Theory Approach to Strategic Decision-making in Space Debris Removal: Insights from Replicator Dynamics

Mohammad Alsuwaidan (UC San Diego), Ahmed Atallah, Aaron J. Rosengren (University of California San Diego)

Evolutionary game theory and population dynamics are applied to manage space debris in this article. The main focus is on evaluating the effectiveness of space debris removal strategies using replicator dynamics, a commonly used model for studying strategy evolution. The article highlights the various applications of this framework, such as predicting the impact of new technologies, understanding the strategic behavior of debris removal entities, and informing decision-making and policy formulation. Overall, evolutionary game theory and population dynamics provide useful tools for analyzing and addressing the challenges of space debris management.

10:45 AM

AAS-354 : Optimizing Active Debris Removal Strategies with Feedback Control for a Sustainable Space Environment

R. Mia Tian (Massachusetts Institute of Technology), **Kai Xi** (Massachusetts Institute of Technology), Giovanni Lavezzi (Massachusetts Institute of Technology), Miles Lifson (Massachusetts Institute of Technology), Simone Servadio (Iowa State University), Richard Linares (Massachusetts Institute of Technology)

Active Debris Removal (ADR) must be strategically deployed to best utilize limited assets. Using the MIT Orbital Capacity Assessment Tool – Source Sink Evolutionary Model (MOCAT-SSEM), our paper demonstrates a feedback proportional-derivative (PD) controller and a nonlinear model predictive controller (NMPC) to select altitudes that optimize ADR. Unlike monte-carlo models, source-sink models allow for the implementation of robust control like NMPC which is effective under uncertainties and disturbances. We evaluate both controllers in various test cases and for objectives such as debris population growth and distribution across altitudes.

11:00 AM

AAS-375 : Reaction Wheel Momentum Control While Electrostatically Tugging Tumbling Space Object

JAMES WALKER (University of Colorado-Boulder), Kaylee Champion (University of Colorado Boulder Autonomous Vehicles Systems Lab), Hanspeter Schaub (University of Colorado)

This paper proposes the use of Coulomb torques to maintain reaction wheel speeds. Charged spacecraft experience electrostatic torques during proximity operations, which can be accounted for with reaction wheels. By adjusting the attitude of one spacecraft relative to the other, the torques can be adjusted to be positive or negative. Because of this, as reaction wheels spin up, the relative orienation of the spacecraft can be changed to allow the wheels to spin down and avoid saturating.

11:15 AM

AAS-410 : Bounding Analysis of Optical Detection of Objects in Low Earth Orbit

Nathan Ré (Advanced Space)

This paper considers recent advancements in detecting and tracking optically faint resident space objects (RSOs) in Earth orbit. Historically, RSO detection was limited to bright objects visible in long exposures. However, new methods using multiple short exposures have been developed. These techniques are effective due to the small number of pixels recording photons in each frame, making faint object detection a computational challenge with various approaches. This study provides an analysis of the minimum detectable size of RSOs using a hypothetical perfect algorithm that stacks a long series of frames along an RSO's trajectory across a camera's field of view.

11:30 AM

AAS-459 : Quantifying Non-Gaussian Neutral Density Uncertainties using Physics-Based Data Assimilation

Nicholas Dietrich (University of Colorado Boulder), Tomoko Matsuo (CIRES)

Forecasting orbit positions in the low Earth orbit (LEO) environment is necessary for avoiding collisions and is increasingly difficult during geomagnetic storms due to highly variable neutral density and the associated uncertainty on atmospheric drag. This study makes an important contribution towards quantifying non-Gaussian neutral density uncertainties, using a new particle filter framework in a much-reduced forcing parameter space. The outcome is a time-varying uncertainty quantification characterizing non-Gaussian uncertainties arising from non-linear storm dynamics. End-to-end uncertainty quantification is accomplished using a Monte Carlo approach, where neutral density uncertainties are mapped to corresponding atmospheric drag and orbit position uncertainties.

11:45 AM

AAS-469 : Dispersion of Targeted Orbital Dust Clouds: Applications to Just-in-time Collision Avoidance

Truman DeWalch (Virginia Tech), Riley Fitzgerald (Virginia Tech), Isaac Payne (Virginia Tech)

Just-in-time collision avoidance (JCA) describes rapid response to prevent a predicted orbital collision, without necessarily removing the offending debris from orbit; this can be accomplished, for example, by deploying a targeted cloud of fine dust to intercept and perturb the orbit of an involved object enough to avoid the anticipated conjunction. We examine the dynamics of such dust clouds along short (hour-scale) intercept trajectories, considering the effects of perturbing forces on the evolving distribution of high-ballistic-coefficient dust grains. We provide guidance on down-selecting to a sufficient set of forces, and demonstrate algorithms for accurately and efficiently propagating uncertain dust distributions.

12:00 PM

AAS-478 : A Monte Carlo Analysis of Density and Accommodation Coefficient Estimation Using a Paddlewheel CubeSat

Craig McLaughlin (University of Kansas Aerospace Engineering), Wyatt Webb (University of Kansas)

A major contributing error to density models is errors in drag coefficient, which include energy accommodation coefficient errors. This paper examines a paddlewheel 3U CubeSat designed to generate sufficient drag force and torque to allow simultaneous estimation of density and accommodation coefficient. To determine the accuracy needed for drag force and torque measurements, a Monte Carlo analysis examines errors in estimated accommodation coefficient and density found for a range of drag force and torque measurement errors, altitudes, CubeSat geometries, and ranges of solar and geomagnetic activity.

12:15 PM

AAS-489 : Designing and Assessing Targeted Dust Cloud Intercepts for Just-in-time Collision Avoidance

Isaac Payne (Virginia Tech), Riley Fitzgerald (Virginia Tech), Truman DeWalch (Virginia Tech)

There is currently little that can be done in response to a predicted conjunction between non-maneuvering objects. This motivates development of just-in-time collision avoidance (JCA) methods, remediations that can be performed after a collision is forecast. One such technique is the deployment of an intercepting dust cloud—if sufficient dust mass impacts the object, its orbit can be perturbed and the conjunction prevented. Given a collision scenario and set of orbital dust assets, we characterize (1) the available intercept trajectories, (2) the impacting dust mass required for each, and (3) techniques for selecting the optimal remediation from among these options.

Orbital Dynamics, Perturbations, and Stability III

Room: Pine, Thursday, August 15

10:30 AM - 12:30 PM

Session Chair(s): Brian Gunter (Georgia Institute of Technology) and Simone Servadio (Iowa State University)

10:30 AM

AAS-236 : Perturbed Restricted Hill 5-Body Problem Applied to a Triple Asteroid System

Tomohiro Ishizuka (ISAE-SUPAERO), Daniel Scheeres (University of Colorado Boulder), StÃ©phanie Lizy-Destrez (ISAE-SUPAERO)

The dynamical environment around a triple asteroid system is highly complex due to the gravitational interactions of the three asteroids, the solar tidal force and the effect of the solar radiation pressure (SRP). In order to investigate the dynamical environment around such asteroid system, this study derives the Perturbed Restricted Hill 5-Body Problem (PRH5BP) which incluses one massive celestial body, three small celestial bodies, one massless body and the SRP. Then, using the PRH5BP, the dynamical environment is explored to find bounded motions.

10:45 AM

AAS-259 : Linear Operator Representation of Dynamical Systems via Classical Perturbation Theory

Miguel Avillez (Purdue University), David Arnas (Purdue University)

This work introduces a methodology for generating linear operators that approximately represent nonlinear systems of perturbed ordinary differential equations. This is done through the application of classical perturbation theory via the Lindstedt-Poincaré expansion, followed by an extension of the space of configuration that guarantees the linear representation of the expanded system of differential equations. This work uses polynomial basis functions, to ensure that such a linear representation exists. The method is applied to the J2 problem, which is analyzed using its osculating formulation. Finally, conditions on the osculating Keplerian elements that produce low-eccentricity frozen orbits are presented.

11:00 AM

AAS-260 : The Dynamics of Particles in Very Close Binary Star Systems

Sofia Lasky-Headrick (The University of Oklahoma), Diogo Merguizo Sanchez (The University of Oklahoma)

Clouds of particles around very close binary star systems, or those with periods on the order of minutes or hours, are studied by considering the dynamics of a single particle in the cloud. The stars are modeled as prolate triaxial ellipsoids, where each star's longest semi-axis is that which is oriented in the direction of the other star. A range of possible systems are considered by varying the orbital and rotation period of the binary stars, the semi-axes of the stars, and the mass distribution between the two stars. The character of particle clouds around very close binaries can impact the the state of understanding of merging binary star systems.

11:15 AM

AAS-288 : A Survey of Oberon Mean Motion Resonant Unstable Orbit Properties and Connections for Uranian Tours

Bhanu Kumar (Heidelberg University), Rodney L. Anderson (Jet Propulsion Laboratory/Caltech)

Heteroclinics between resonances enable propellant-free changes of semimajor axis, and are important for outer planet tour design. While resonances have been studied for many Jovian and Saturnian moons, similar analyses for the Uranus system are lacking. In this study, we characterize resonant orbits for Uranus' outermost large moon, Oberon. We first compute various such orbits and their stable/unstable manifolds in the Uranus-Oberon planar circular restricted 3-body problem, demonstrating connections between resonances varying with energy level. Then, given Titania's proximity to many Oberon interior resonances, we study Oberon resonant orbits in a restricted 4-body model including Titania, finding secondary resonant phenomena.

11:30 AM

AAS-309 : Propellantless Orbit and Attitude Maintenance Strategy for Asteroid Missions

Shota Kikuchi (National Astronomical Observatory of Japan), Yuichi Tsuda (Japan Aerospace Exploration Agency)

The orbital and attitude motions around asteroids are significantly perturbed and coupled with each other, necessitating frequent maintenance maneuvers. This research introduces a propellantless strategy for maintaining spacecraft motion by leveraging environmental disturbances, such as solar radiation pressure and asteroid gravity. The key idea is to repeatedly implement the following three operations: sun-synchronous coupled orbit-attitude motion, orbit correction via solar sailing, and momentum unloading using environmental torques. The proposed method does not require specific devices except for reaction wheels, making it suitable for any asteroid mission. Through both analytical and numerical analyses, we validate this novel operation concept.

11:45 AM

AAS-317 : Design of Lunar Frozen Orbit Considering Lunar Harmonics and 3rd Body Effects

Grigory Nikitin (Texas A&M University), Kyle T. Alfriend (Texas A&M University)

The new analytic theory by Mahajan and Alfriend lets us use more lunar gravitational harmonics for orbit analysis, compared to many papers where only the J2 coefficient is used. In this paper, the 3rd body effects of the Earth were also included in the theory to improve the accuracy. The step-by-step derivations of the Hamiltonian averaging process and generating functions are presented, as well as the equations of motion. This new comprehensive analytic theory is then applied to determine frozen orbits.

12:00 PM

AAS-318 : Comparative Analysis of Analytical and Data-Driven Koopman Operators for the J2 Problem With Atmospheric Drag

Christian Hofmann (Massachusetts Institute of Technology), **Giovanni Lavezzi** (Massachusetts Institute of Technology), Di Wu (MIT), Simone Servadio (Iowa State University), Richard Linares (Massachusetts Institute of Technology)

We advance the Koopman operator theory (KOT), a method to transform a nonlinear dynamical system into a linear one, for the perturbed motion of a satellite around a central body. Our approach introduces a novel numerical technique utilizing quadrature points for training data and employing differentiated weighting of training samples compared to the state-of-the-art Extended Dynamic Mode Decomposition method. Additionally, KOT is extended to encompass the motion of a satellite subject to atmospheric drag, enabling the analytical prediction of future states. Our third contribution entails an extensive assessment of analytical and numerical KOT methods, including a Monte Carlo analysis to explore the impact of selected parameters on convergence and accuracy.

12:15 PM

AAS-333 : Dynamics of a Particle around a Non-Homogeneous Straight Segment

Elisa Martinez Robles (Universidad del Bío-Bío)

We analyze the dynamics of an infinitesimal mass in a gravitational field generated by a rotating, non-uniform, straight segment. We derive the potential in closed form by employing a parametrically defined linear density. We study the existence and linear stability of relative equilibria. Additionally, for the case of a fixed straight segment, we determine a family of circular orbits. Moreover, we also study the singular solutions for the fixed segment and show that any solution not globally defined over time implies that the particle's approach towards the segment eventually converges to zero distance. Within the one-dimensional problem along the ξ-axis, it is observed that all singularities arise due to collisions.

Space Situational Awareness, Conjunction Analysis, and Collision Avoidance II
Room: Centennial F, Thursday, August 15
10:30 AM - 12:30 PM
Session Chair(s): Oscar Fuentes-Muñoz (NASA Jet Propulsion Laboratory/Caltech) and Mark Vincent (Raytheon)

10:30 AM
AAS-125 : Learning Hyperplanes for Multi-Agent Collision Avoidance in Space
Fernando Palafox (The University of Texas at Austin), Yue Yu (The University of Texas at Austin), David Fridovich-Keil (The University of Texas at Austin)

A core challenge of multi-robot interactions is collision avoidance among robots with potentially conflicting objectives. We propose a game-theoretic method for collision avoidance based on rotating hyperplane constraints. These constraints ensure collision avoidance by defining separating hyperplanes that rotate around a keep-out zone centered on certain robots. Since it is challenging to select the parameters that define a hyperplane without introducing infeasibilities, we propose to learn them from expert trajectories. We validate our method by learning hyperplane parameters from noisy expert trajectories and then apply it to a collision avoidance scenario in space.

10:45 AM
AAS-154 : International Sharing of Satellite Tracking Data for Improved Orbital Safety
Felix R. Hoots (Aerospace Corporation), Matt Hejduk (The Aerospace Corporation), Valentin Baral (Centre National d'Ã‰tudes Spatiales), Florian Delmas (CNES), Alejandro Cano Sanchez (GMV), Santiago Martinez (GMV)

Data sharing among different Space Situational Awareness (SSA) data collectors/providers is frequently discussed as a mechanism to improve the accuracy and precision of orbital safety products. To understand the improvements achieved through sharing at the measurement level, the US Office of Space Commerce and the European Union Space Surveillance and Tracking (EUSST) have performed orbit determination with their own observations, the other entity's observations, and with both observation data sets combined. This study investigates the benefits to space safety using a set of real-world conjunctions with significant risk that had been processed by both the US OSC and EU SST.

11:00 AM
AAS-155 : Incorporating Low-Thrust Propagation and Improved Covariance Realism for Enhanced Simulation of Future Space Object Populations
Clifford Stueck (Georgia Institute of Technology), Surya Venkatram (Georgia Institute of Technology Space Systems Design Lab), Alaric Gregoire (Georgia Institute of Technology), Brian Gunter (Georgia Institute of Technology), Timothy Murphy (Aerospace Corporation)

Recent advancements to a simulation environment integrate low-thrust maneuvers, updated line-of-sight tracking, and covariance modeling in space simulation, enhancing collision avoidance and operational efficiency. Validation using a future space catalog helps to refine these processes, optimizing for conjunction count and delta-v. Low-thrust maneuver capabilities are tested using real GPS data to ensure realistic propagation and thrust. This research not only improves spacecraft simulation but also bolsters space domain awareness for sustainable space exploration amidst growing congestion and competition.

11:15 AM

AAS-193 : Reachability Set Search for Lost Custody of Maneuvering Spacecraft Leveraging Normal Form Methods

David Schwab (The Pennsylvania State University), Roshan Thomas Eapen (The Pennsylvania State University), Puneet Singla (The Pennsylvania State University)

The reachability set search method is an algorithm to search for a lost spacecraft given assumptions on maneuver parameters. It takes a particle filter-like approach to approximate the time evolution of the probability density function. A polynomial approximation to the reachability at measurement time is utilized for efficient propagation, and an optimal sensor action is defined. However, due to the dynamics of cislunar space, the approximation will lose accuracy quickly. This work leverages the normal form coordinates of the circular restricted three-body problem to define many local approximations to the reachability set to increase accuracy of the search method.

11:30 AM

AAS-219 : Uncertainty Propagation and Estimation in Highly Eccentric Perturbed Environments; Application and Analysis of the Gauss von Mises Distribution

Ryne Beeson (Princeton University), Pradipto Ghosh (Johns Hopkins University Applied Physics Lab)

Propellant efficient transfers of spacecraft to the lunar realm often involve highly eccentric transfers following trans-lunar injection burns. It is not uncommon to lose observation of these cislunar objects near apoapsis. Accurate and efficient uncertainty propagation is then necessary to restore custody of the object. In this paper, we analyze the applicability of a number of uncertainty propagation methods for these highly eccentric scenarios, with motivation from the CAPSTONE/Photon mission. We focus on the performance and behavior of the Gauss von Mises distribution, standard techniques, and the modified Equidistant Cylindrical coordinates. Statistical metrics, including goodness-of-fit, are presented alongside qualitative analysis.

11:45 AM

AAS-237 : Assessment of Data Quality Requirements for US Space Traffic Management

Timothy Murphy (Aerospace Corporation), Kerstyn Auman (The Aerospace Corporation), Matt Hejduk (The Aerospace Corporation), Zachary Sibert (Naval Research Laboratory), Patric Hoskins (Naval Research Laboratory), Alan Segerman (U.S. Naval Research Laboratory)

The Department of Commerce Office of Space Commerce is in the process of standing up an independent space traffic management system. This system is in-tended to provide space traffic management services to satellite operators as a public service, including conjunction assessment. This system may rely on both current Department of Defense data alongside commercially provided services and data. In order to effectively plan this system, The Aerospace Corporation was asked to assess the current performance of this system and determine how best to include commercial data. While data assessment strategies will continue to evolve, the current performance implies there are two distinct value points for supplemental commercial data.

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