# 33rd AAS/AIAA Space Flight Mechanics Meeting, Austin, Texas, January 15-19 2023

American Astronautical Society

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## Conference Chairs

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# Conference Information

## General Information

The 33rd AAS/AIAA Space Flight Mechanics Meeting, hosted by the American Astronautical Society (AAS) and cohosted by American Institute of Aeronautics and Astronautics (AIAA) will be held January 15-19, Austin, Texas. The conference is organized by the AAS Space Flight Mechanics Committee and the AIAA Astrodynamics Technical Committee.

Online conference registration can be accessed at

https://www.xcdsystem.com/aas/attendee/index.cfm?ID=SB9aqa8

| Registration Type | Early (On or before Dec 16, 2022) | Regular (After Dec 16, 2022 through Jan 13, 2023) | Walkups (After Jan 13, 2023) |
|---|---|---|---|
| Full Registration - Current Member (AAS or AIAA) | $750 | $850 | $950 |
| Full Registration - Non-member, includes one-year AAS membership | $850 | $950 | $1050 |
| Student Registration - Current Member (AAS or AIAA) | $450 | $550 | $650 |
| Student Registration - Non-member, includes one-year AAS membership | $495 | $595 | $695 |
| Retiree Registration - Current Member (AAS or AIAA) | $450 | $550 | $650 |
| Retiree Registration - Non-member, includes one-year AAS membership | $500 | $600 | $700 |

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 shown in the above table.

**Registration Cancellations and Refunds**: The cut-off date for refunds after registration cancellation is Thursday, January 12th.

**Coronavirus (COVID-19) Considerations:** The conference organizers have decided to hold the 33rd AAS/AIAA Space Flight Mechanics Meeting in person at The LINE Austin hotel in Austin, TX. Please monitor the conference website for updates on the conference guidelines. We will abide to any applicable local, state, and federal laws.

## Special Event Information

On **Sunday** there will be a catered welcome reception from 6-8 PM with food and drinks at the conference hotel.

On Monday and Tuesday at around 5 PM, after the regular sessions, we will have special events as described below. Both of these events will be followed with a light reception.

On **Monday**, in celebration of the Martin Luther King, Jr. holiday, we will have a special panel discussion on the role of mentorship and diversity in strengthening our Astrodynamics community entitled:

*Each One Teach One: Building a Better and Stronger Astrodynamics Community*

The panel moderator is Dr. Powtawche Valerino (NASA-Marshall), whilst confirmed panelists include Prof. Kathleen Howell (Purdue), Prof. Hanspeter Schaub (Colorado), Ms. Heather Koehler (NASA-Marshall), and Mr. Amalaye Oyake (Blue Origin, TBC).

On **Tuesday** we will have a special presentation on NASA's DART mission, led by Dr. Julie Bellerose (JPL). After this, the Breakwell Student Travel Awards will be given out.

Each evening we will help organize groups of participants to go out and explore the local Austin music and food scene. There are dozens of music venues within walking distance of the hotel and hundreds of food options, from BBQ to TexMex to Thai, and everything in between. We will have a curated list of music venues and eating establishments to help guide all attendees, as well as sign-up sheets for groups to form.

The receptions on Sunday, Monday, and Tuesday are included with every registration (Full, Student, and Retiree).

You can purchase additional tickets for your guest to attend all of the receptions during the online registration process as follows:

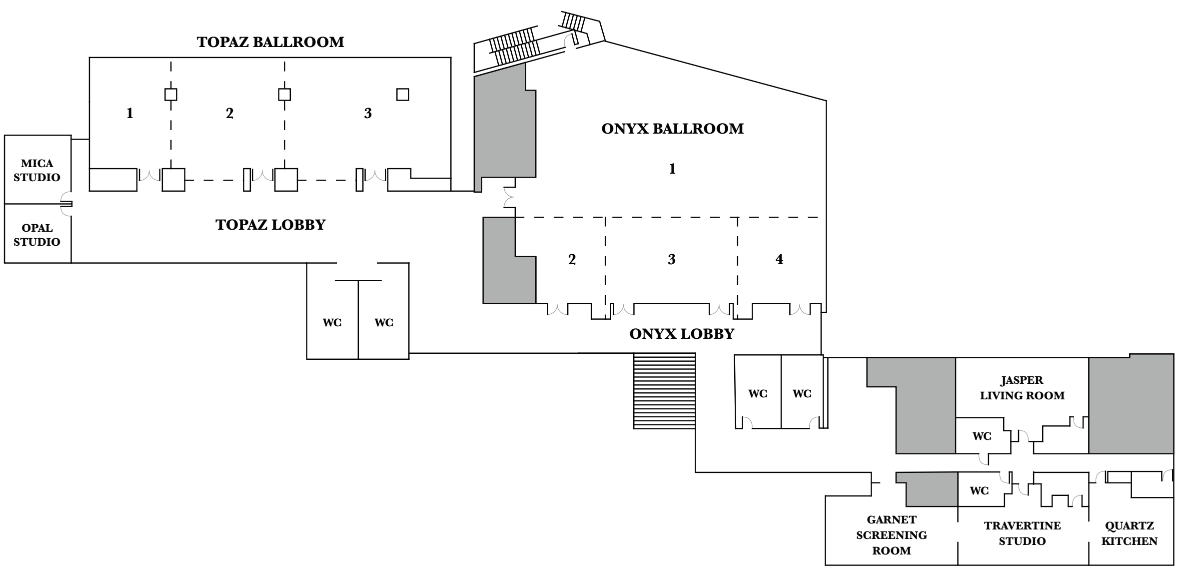
| | |
|---|---|
| 1x extra Reception ticket (Sunday, Monday, Tuesday) | $125 |
| 2x extra Reception tickets (Sunday, Monday, Tuesday) | $250 |

## 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 Venue

The LINE Austin Hotel
111 East Cesar Chavez
Austin, Texas 78701 USA
Phone:+1 512-478-9611


**Meeting room layout**

**Parking:** Daily parking at The Line is available for $15 / day, not including overnight. You must mention that you are attending the conference when you drop your car off.

# Additional Technical Information

## Conference Proceedings

We are delighted to welcome Springer Nature as new 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. The charge is $140 per extra proceedings for download.

## Presentations

Author presentations (preferably in ppt or pdf format) will be submitted through a web-based system and are due by **Tuesday January 10th**, 2023, 23:59:59 Eastern Time. Each presentation is allocated a 20 minute time slot: approximately 15 minutes for the presentation itself and 5 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; however, each presenter is ultimately responsible for having the necessary computer and software available to drive the presentation. 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 **Thursday January 5th**, 2023, 23:59:59 Eastern Time. A final paper upload is due after the conference, 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.

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

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## 33rd AAS/AIAA Space Flight Mechanics Meeting: Event and Session Summary

| Day | Start | End | Event / Conference Session | Room | Session Chair |
|---|---|---|---|---|---|
| **Sunday 1/15/23** | 6:00 PM | 8:00 PM | **Opening Reception** | Onyx Ballroom | |
| **Monday 1/16/2023** | 8:00 AM | 12:00 PM | Orbit Determination and Space Surveillance Tracking 1 | Onyx 2-3 | Brandon Jones |
| | 8:00 AM | 12:00 PM | Orbital Debris and Space Environment | Topaz 1 | David B. Spencer |
| | 8:00 AM | 12:00 PM | Trajectory/Mission/Maneuver Design and Optimization 1 | Topaz 2 | Powtawche Valerino |
| | 8:00 AM | 12:00 PM | Rendezvous, Relative Motion, Proximity Missions, and Formation Flying 1 | Topaz 3 | Siamak Hesar |
| | 12:00 PM | 1:30 PM | *AAS/AIAA Joint Technical Committee Meeting* | Onyx 1 | |
| | 1:30 PM | 4:50 PM | Trajectory/Mission/Maneuver Design and Optimization 2 | Onyx 2-3 | Jin Haeng Choi |
| | 1:30 PM | 4:50 PM | Dynamical Systems Theory Applied to Space Flight | Topaz 1 | David Canales Garcia |
| | 1:30 PM | 4:50 PM | Spacecraft Guidance, Navigation and Control 1 | Topaz 2 | Angela Bowes |
| | 1:30 PM | 4:50 PM | Asteroid and Small Body Missions | Topaz 3 | Paul Thompson |
| | 5:15 PM | 6:15 PM | ***Each One Teach One: Building a Better and Stronger Astrodynamics Community*** (Panel Discussion led by Dr. P. Valerino) | Onyx Ballroom | Dan Scheeres<br>Sonia Hernandez |
| | 6:15 PM | 7:15 PM | **Reception** | Onyx Ballroom | |
| **Tuesday 1/17/2023** | 8:00 AM | 12:00 PM | Cislunar Space Missions and Operations 1 | Onyx 2-3 | Diane Davis |
| | 8:00 AM | 12:00 PM | Earth Orbital Missions and Studies | Topaz 1 | Arnaud Boutonnet |
| | 8:00 AM | 12:00 PM | Space Situational Awareness, Conjunction Analysis, and Collision Avoidance 1 | Topaz 2 | Piyush Mehta |
| | 8:00 AM | 12:00 PM | Rendezvous, Relative Motion, Proximity Missions, and Formation Flying 2 | Topaz 3 | Robert Melton |
| | 12:00 PM | 1:00 PM | *AIAA Committee Meeting* | Onyx 1 | |
| | 1:00 PM | 1:30 PM | **Plenary Talk: Canadian Space Agency** by Dr. I. Jean (CSA) | Onyx 2-3 | Dan Scheeres |
| | 1:30 PM | 3:10 PM | CubeSat and SmallSat Missions | Onyx 2-3 | Arnaud Boutonnet |
| | 3:30 PM | 4:30 PM | DART Navigation | Onyx 2-3 | Ricardo Restrepo / Sonia Hernandez |
| | 1:30 PM | 4:50 PM | Attitude Dynamics, Determination and Control 1 | Topaz 1 | Dr. Peter Lai |
| | 1:30 PM | 4:50 PM | Trajectory/Mission/Maneuver Design and Optimization 3 | Topaz 2 | Stefano Campagnola |
| | 1:30 PM | 4:50 PM | Spacecraft Guidance, Navigation and Control 2 | Topaz 3 | James Thorne |
| | 5:15 PM | 6:15 PM | **Special Talk: *DART: Navigating to Obliteration*** by Dr. J. Bellerose (JPL)<br>**Presentation of Breakwell Student Travel Awards** | Onyx Ballroom | Dan Scheeres<br>Sonia Hernandez |
| | 6:15 PM | 7:15 PM | **Reception** | Onyx Ballroom | |
| **Wednesday 1/18/2023** | 8:00 AM | 10:00 AM | Atmospheric Re-entry Guidance and Control | Onyx 2-3 | Davide Guzzetti |
| | 10:20 AM | 12:00 PM | Machine Learning and Artificial Intelligence Applied to Space Flight Problems 1 | Onyx 2-3 | Hang Woon Lee |
| | 8:00 AM | 12:00 PM | Orbital Dynamics, Perturbations, and Stability | Topaz 1 | Atri Dutta |
| | 8:00 AM | 12:00 PM | Trajectory/Mission/Maneuver Design and Optimization 4 | Topaz 2 | Nicholas Bradley |
| | 8:00 AM | 12:00 PM | Spacecraft Autonomy | Topaz 3 | Keith LeGrand |
| | 12:00 PM | 1:30 PM | *AAS Committee Meeting* | Onyx 1 | |
| | 1:30 PM | 4:50 PM | Orbit Determination and Space Surveillance Tracking 2 | Onyx 2-3 | Christopher Roscoe |
| | 1:30 PM | 4:50 PM | Machine Learning and Artificial Intelligence Applied to Space Flight Problems 2 | Topaz 1 | Davide Guzzetti / Davide Amato |
| | 1:30 PM | 4:50 PM | Trajectory/Mission/Maneuver Design and Optimization 5 | Topaz 2 | Jason Leonard |
| | 1:30 PM | 3:10 PM | Spacecraft Guidance, Navigation and Control 3 | Topaz 3 | Casey Heidrich |
| | 6:00 PM | 7:30 PM | *CAS Meeting* | Topaz 1 | |
| | 6:00 PM | 7:30 PM | *TAS Meeting* | Topaz 2 | |
| | 6:00 PM | 7:30 PM | *WAS Meeting* | Topaz 3 | |
| **Thursday 1/19/2023** | 8:00 AM | 12:00 PM | Space Situational Awareness, Conjunction Analysis, and Collision Avoidance 2 | Garnet | Isabelle Jean |
| | 8:00 AM | 12:00 PM | Attitude Dynamics, Determination and Control 2 | Topaz 1 | Davide Guzzetti |
| | 8:00 AM | 12:00 PM | Cislunar Space Missions and Operations 2 | Topaz 2 | Carmine Giordano |
| | 8:00 AM | 12:00 PM | Rendezvous, Relative Motion, Proximity Missions, and Formation Flying 3 | Topaz 3 | Jeffrey Stuart |

## Monday Evening, January 16

### *Each One Teach One: Building a Better and Stronger Astrodynamics Community*

**5:15-6:15PM: Panel Discussion in the Onyx Ballroom**

**6:15-7:15: Reception in the Onyx Ballroom**

To celebrate Martin Luther King, Jr. Day as a day of national service, we will have a special panel discussion on the role of mentorship and service in strengthening our Astrodynamics community. We have a panel of distinguished academic, NASA and private aerospace representatives who will share their own experiences and join together in a larger discussion.

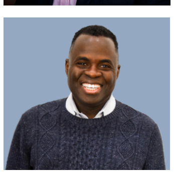
### Panel Moderator

Dr. Powtawche Valerino works at the NASA-Marshall Space Flight Center in the Guidance, Navigation, and Mission Analysis Branch. She supports NASA's Space Launch System, Human Landing System, and Artemis Campaign Development Programs. Prior to her current position she was a flight path control analyst at JPL for over 13 years and was on the navigation teams for the Cassini-Huygens, Europa Clipper, and Parker Solar Probe missions. Powtawche holds a bachelor's degree in mechanical engineering from Stanford University, and a master's and doctoral degree in mechanical engineering with a specialty in aero-astronautics from Rice University.

### Panel Participants

Prof. Kathleen Howell is the Hsu Lo Distinguished Professor at Purdue University in the School of Aeronautics and Astronautics. She is known for her contributions to dynamical systems theory applied to spacecraft trajectory design which led to the use of halo orbits in multiple NASA space missions. She is a member of the National Academy of Engineering, a Member of the International Academy of Astronautics, and a Fellow of the AAS and AIAA. In acknowledgment of her many achievements, Discover magazine recognized her in 2002 as one of the 50 most important women in science.

Ms. Heather Koehler currently serves as the NASA Technical Fellow for Flight Mechanics. Her background includes developing guidance, navigation and control flight software for the Space Shuttle Program including real-time operational support to many Shuttle missions. She has supported payload software development and testing for the ISS and developed the Agency's first directional sporadic meteoroid model. Ms. Koehler has served as the Vehicle Management Discipline Lead for the SLS and as Branch Chief in the Guidance, Navigation and Mission Analysis Branch including details at the Flight Mechanics Division level.



Mr. Amalaye Oyake is Senior Flight Software Engineer at Blue Origin working on flight software for Orbital Reef. His prior work at NASA JPL included 'Space Internet' standards, CCSDS working groups, the Mars Exploration Rover, Mars Science Laboratory, and payloads for the International Space Station.

Dr. Hanspeter Schaub is chair of the University of Colorado aerospace engineering sciences department and holds the Schaden leadership chair. His research interests are in astrodynamics, relative motion dynamics, charged spacecraft motion as well as spacecraft autonomy. Dr. Schaub has been the ADCS lead in the CICERO mission and the ADCS algorithm lead on a Mars mission. He is a fellow of AIAA and AAS, and has won the AIAA/ASEE Atwood Educator award, AIAA Mechanics and Control of Flight award, as well as the Collegiate Educator of the Year for the AIAA Rocky Mountain section.

**Tuesday Afternoon, January 17**

## Canadian Space Agency Overview

Dr. Isabelle Jean (CSA)

**1:00-1:30PM: Onyx 2/3**

Canada pioneered space utilization because of the need to communicate throughout its territory and observe its great land, most of which is hard to reach and far in the North. Did you know that it is also involved in space exploration, Earth observation and space science? Canada found its own way to be involved in the greatest space endeavors throughout the years, and also in future big projects like the Lunar Gateway. This presentation is about a few CSA/Canada space facts, the projects CSA is involved in or is leading and what it is like to work there.

Isabelle Jean completed a Bachelor and Master Degree in Electrical Engineering at the Université de Sherbrooke in 2004, specializing in the control of Low Earth Orbit for low thrust spacecraft. She then worked for more than ten years at the Canadian Space Agency as a Payload Operations Engineer for the International Space Station before starting a PhD at McGill University in Mechanical Engineering, which she completed in May 2020. There, she studied the dynamics of spacecraft in a binary asteroid environment. She now works as a Systems Engineer for Earth observation missions at the Canadian Space Agency.

**Tuesday Evening, January 17**

***DART: Navigating to Obliteration***

Dr. Julie Bellerose (JPL)
Onyx Ballroom

**5:15-6:00PM: DART Talk**
**6:00-6:15PM: Breakwell Student Travel Awards**
**6:15-7:15: Reception in the Onyx Ballroom**

DART is NASA's demonstration of an asteroid deflection using a kinetic impactor. The spacecraft launched aboard a SpaceX's Falcon 9 on November 24th 2021, on a direct collision with the binary asteroid system Didymos planned for September 26th 2022. By impacting the small moon, Dimorphos, DART's objective was to alter the moon's orbit about the larger asteroid by several minutes.

The navigation of a ballistic mission is usually relatively simple. Other than heading to a violent demise, this mission had a number of unconventional aspects which gave the navigation team interesting challenges: a tight propellant budget for part of the mission, no reaction wheels which resulted in a noisy spacecraft with the Nav team having to rely heavily on Delta Differential One-way Ranging measurements to identify off line-of-sight delta-V, and critical operations in the last 30 days of the mission under a new thrusting control mode regime. Optical navigation was a critical element in the success of this mission, contributing to the determination of the spacecraft and target ephemerides for refined targeting maneuvers. After strategic decisions in the final weeks of the missions, DART could have comfortably hit the larger asteroid, Didymos, which increased the probably of impact with its moon Dimorphos.

Dr. Julie Bellerose graduated with a BEng in Mechanical engineering from McGill University and a PhD in Aerospace engineering from the University of Michigan. She is based at the Jet Propulsion Lab since 2013, and has supported navigation of Cassini, Hayabusa2, Rosetta, and Osiris-Rex. Julie was the DART Navigation lead, which hit the asteroid Dimorphos in September 2022 as a planetary defense demonstration mission.

# Conference Technical Presentation Schedule

# Monday, January 16

## Session: Orbit Determination and Space Surveillance Tracking 1

**Room: Onyx 2-3, Time: 08:00 AM-10:00 AM**

Session Chair: Brandon Jones (The University of Texas at Austin)

**08:00 AM**

**109: Absolute and Autonomous Navigation for Distributed Space Systems with Relative Measurements**

*Jesse Greaves* and Daniel Scheeres*

Autonomous navigation for distributed space systems can be completely solved for by using relative measurements between vehicles, thereby removing any need for ground-based measurements or orbit determination. We prove that this is possible because non-linearities produce information on the absolute state, while first order motion produces information on the relative state. This navigation methodology is then simulated in two and three body scenarios to demonstrate its use and applicability. Because of the reliance on non-linearities it is found that this navigation method excels when system motion is highly differential, but faulters as the differential decreases.

**08:20 AM**

**157: A GLMB FILTER FOR SPACE OBJECTS WITH CONTROL METRIC BASED MANEUVER DETECTION**

*Guillermo Escribano*, Brandon Jones, Manuel Sanjurjo-Rivo, Jan Siminski, Alejandro Pastor and Diego Escobar*

The increasing number of active satellites in Earth orbit drives the need to automate Space Surveillance and Tracking activities. Satellite maneuvers pose a significant challenge in this regard, demanding robust and adaptive filters for data association and custody maintenance purposes. The GLMB filter provides a closed form solution to the multi-target tracking problem in a Bayesian framework and has been successfully applied to space object tracking. Within this work we propose a GLMB implementation where maneuvers are characterized in some control metric space, as opposed to general approaches based on process noise.

**08:40 AM**

**159: Investigation on Autonomous Orbit Determination in Cislunar Space via GNSS and Horizon-Based Measurements**

*Daniel Qi* and Kenshiro Oguri*

A robust yet affordable autonomous orbit determination system must be in place before increasing the traffic of spacecraft in cislunar space. Two methods of autonomous cislunar orbit determination analyzed in this paper are GNSS signals and horizon-based optical navigation. A Monte Carlo simulation of the dynamical model is conducted to estimate the distribution of root-mean-square errors of each measurement. Preliminary results show that more unstable Halo orbits around L2 can benefit significantly by combining the two measurements, while less unstable orbits closer to the Moon may see no improvement in orbit determination by combining optical measurements.

**09:00 AM**

**193: GPS-Based Precise Orbit Determination of LEO Satellites Using Space-based Double-Differenced Observations**

*Zhigui Kang*, Srinivas Bettadpur, Himanshu Save and Peter Nagel*

One of important GPS applications in space is precise orbit determination (POD) of Low-Earth Orbiting (LEO) satellites. Thousands of LEO satellites are currently in orbit. One of the challenges is how to efficiently and precisely determine the orbits to satisfy the relative and absolute accuracy needs of missions. Currently, GNSS-based POD of LEO satellites can be performed using either un-differenced (UD) or ground-based double-differenced (DD) observations. For some formation flying satellite missions, the absolute orbit accuracy requirements are not as stringent as the relative requirements. Based on this motivation, we investigated the GPS-based LEO POD using space-based DD observations.

**09:20 AM**

**392: Orbital Predictions and Spacecraft Observations Through Commercial Telescopes**

*Paula do Vale Pereira*, Keefe Kamp, Hector De Castillo, Jason Kenney and Alexander Brunette*

Two Line Elements (TLEs) are public strings of information that tell the orbital elements of a spacecraft and allow operators and engineers to locate and communicate with their spacecraft. Unfortunately, TLEs have not been frequently used as educational tools when teaching space flight mechanics. In this paper, we will describe how undergraduate students used TLEs to calculate the azimuth and elevation of spacecrafts for the geolocation of the university, and then used commercial 8” telescopes to look at the point of maximum elevation of their selected spacecraft at the predicted moment, observing the satellite pass for approximately one second.

## Session: Orbital Debris and Space Environment

**Room: Topaz 1, Time: 08:00 AM-10:00 AM**

Session Chair: David B. Spencer (The Aerospace Corporation)

**08:00 AM**

**125: An Investigation On Space Debris Of Unknown Origin Using Proper Elements And Neural Networks**

*Di Wu* and Aaron Rosengren*

We have shown the first large scale proper elements calculation in the circumterrestrial space and the first debris families analysis. Satellite proper elements are developed to analytically connect its quasi-constancy feature with long-term dynamics evolution. A simple deep neural networks is introduced to answer the basic question of whether any two space debris are from the same family or not. This introduces flexible nonlinear criteria and replaces the threshold criteria in DBSCAN. Space objects with unknown origins and their proper elements are investigated with this neural networks augmented DBSCAN. We further show the existence of debris families in analyst objects for the first-time.

**08:20 AM** **240: Monte Carlo methods to model the evolution of the LEO population**

*Daniel Jang*, Davide Gusmini, Peng Mun Siew, Andrea D'Ambrosio, Simone Servadio, Pablo Machuca and Richard Linares*

A Monte-Carlo method for simulating the LEO environment is developed and described in this work. Over the past couple of decades, a number of models have been developed by space agencies and private entities. The MIT Orbital Capacity Analysis Tool (MOCAT) has expanded to include the MOCAT-MC tool, which propagates the LEO RSO’s orbits and models their interaction with one another to understand the population evolution of the LEO environment.

**08:40 AM** **164: Optimal Target Selection for an Active Debris Removal Mission**

*Simone Servadio*, Theo St Francis, Nihal Simha, Davide Gusmini, Daniel Jang, Andrea D'Ambrosio and Richard Linares*

The first step of any Active Debris Removal (ADR) mission is the selection of the target. The optimal choice is to find the most dangerous debris that can be removed considering the chaser spacecraft requirements and mission constraints, i.e., Launcher's Orbital Transfer Vehicle (OTV) Orbiter. After creating a catalog of the current space population in Low Earth orbit (LEO), MIT Monte Carlo Orbital Capacity Assessment Tool (MOCAT-MC) is used to simulate and predict the future space environment. A novel performance index to quantify the criticality of each debris is presented, and a list of ranked optimal targets is provided.

**09:00 AM** **274: Space debris cloud propagation through finite volume method**

*Lorenzo Giudici* and Camilla Colombo*

The extension of the debris evolutionary models to any orbital regime is crucial to assess the future evolution of the space environment. When extending the continuum approach to any non-linear dynamics, the bottleneck is given by the computational cost. This paper proposes a novel approach to propagate a density distribution through finite volume method applied to the continuity equation, which is integrated analytically over a control volume. The model aims to provide both a more realistic variation of the density over space and time, and a higher computational efficiency, as the density distribution is directly propagated.

**09:20 AM** **275: Defining a framework for cislunar space debris mitigation using large solution scans from families of periodical solutions**

*Paolo Guardabasso*, Despoina K. Skoulidou, Francesca Letizia, Stijn Lemmens, Lorenzo Bucci and Stéphanie Lizy-Destrez*

This paper focuses on space debris mitigation techniques and analyses applied to cislunar space, due to the growing interest in lunar exploration and the increase in traffic that will likely follow in the coming years. Two main scenarios are analyzed: disposal maneuver scans and fragmentation events. In both cases, starting points are derived from periodical solutions of the Circular Restricted Three Body Problem, which are then corrected in the Sun-Earth-Moon ephemeris problem. Trajectories are then propagated for long times (up to 100 years) to assess and characterize propagation outcomes with respect to present debris guidelines.

**09:40 AM** **375: Investigation of Fragmentation Events in the Cislunar Domain**

*Arly Black* and Carolin Frueh*

As space operations expand into the cislunar regime, understanding the debris-related consequences of cislunar fragmentation events is essential. This work developed and applied a simulation based on the NASA Standard Breakup Model to assess the fragmentation process in the cislunar realm. Once characterized by the SBM, each fragment is propagated, using the CR3BP approximation and multiple orbit types, to examine the dynamics of the fragments over time and to probe for patterns in their behaviour. Observations reveal that debris particles do not remain bounded near their parent orbit but rather traverse far-reaching and diverse orbits.

## Session: Rendezvous, Relative Motion, Proximity Missions, and Formation Flying 1

### Room: Topaz 3, Time: 08:00 AM-10:00 AM

Session Chair: Siamak Hesar (Kayhan Space Corp)

**08:00 AM** **142: Safety in Forced Motion Guidance for Proximity Operations Based on Relative Orbital Elements**

*Giacomo Borelli*, Gabriella Gaias and Camilla Colombo*

The operations of a chaser flying in proximity to another spacecraft, often uncooperative and non-collaborative, must take the feature of flight safety as paramount. In this work, the problem of trajectory safety is considered in the guidance design for the terminal guidance phases of a rendezvous to a non-collaborative object. Novel safety formulations based on relative orbital elements are introduced to cope with the forced motion phases, including concepts of passive abort safety and active collision safety at guidance level. These formulations are exploited within a sequential convex programming algorithm to efficiently compute the reconfiguration and synchronisation nominal trajectories.

**08:20 AM** **148: Post-Docking Spacecraft Dynamics Using Baumgarte Stabilization**

*João Vaz Carneiro*, Andrew Morell and Hanspeter Schaub*

This paper proposes a modular approach to accurately describe the dynamics of two spacecraft docked to each other. Taking advantage of classic control techniques, the dynamics of two docked spacecraft, each with its own reaction wheels or flexible structures, can be simulated by numerically enforcing the constraints between these two complex bodies. This numerical approach to model constrained motion between two complex vehicles shows promising results, with constraint violations that are multiple orders of magnitude smaller than the size of each spacecraft and the ability to apply orbital and attitude maneuvers while enforcing the constraints successfully.

**08:40 AM**

### 199: Genetic Fuzzy System-based Control for Final Approach of Spacecraft Rendezvous and Proximity Operations

*Daegyun Choi*, Donghoon Kim and Henzeh Leeghim*

On-orbit servicing has been receiving great attention thanks to the advancement of space technologies. To support such missions, rendezvous and proximity operations are necessary. This work proposes a control model for the final approach of rendezvous based on a fuzzy inference system under relative orbit dynamics. The proposed controller determines the control inputs of a chaser spacecraft based on the relative states. By training the controller using a genetic algorithm, the proposed controller learns the ability to produce a near-optimal control signal. Then, multiple scenarios are tested to validate the performance of the trained controller.

**09:00 AM**

### 212: Fuzzy-Aided Closed-Loop Inverse Kinematics Control for Capturing a Tumbling Satellite

*Sathya Karthikeyan*, Anirudh Chhabra, Daegyun Choi and Donghoon Kim*

The desirability of using space manipulators for on-orbit capturing has invoked research interests in various aspects. This paper focuses on capturing a rotating satellite using a single-arm manipulator mounted on the servicing spacecraft. A Fuzzy-Inference System-aided Closed Loop Inverse Kinematics control methodology is proposed to optimally maneuver the manipulator arm for capture while satisfying certain constraints. The proposed method is then validated using a simulation study which considers the orbital motions and the dynamics of the manipulator, servicer spacecraft, and target satellite.

**09:20 AM**

### 111: Nonlinear Adaptive Angle-Only Relative Navigation on Perturbed Eccentric Orbits

*Yazan Chihabi* and Steve Ulrich*

A novel angle-only relative navigation algorithm that utilizes both the extended and unscented Kalman filters for spacecraft relative motion is proposed in this paper. Specifically, the algorithms take advantage a process model that based on exact Hamiltonian dynamics that includes the perturbations along with an exact measurement model that maps orbital elements to angle measurements. The proposed solution is tested in highly elliptical orbit with the resulting the effectiveness of the proposed measurement and process models over relative orbital elements based models, where the proposed model resulted in orders of magnitude increase in accuracy.

## Session: Trajectory/Mission/Maneuver Design and Optimization 1

### Room: Topaz 2, Time: 08:00 AM-10:00 AM

Session Chair: Powtawche Valerino (NASA Marshall Space Flight Center)

**08:00 AM**

**114: No Initial Guess Required: Rapidly Computing the Feasible Set of Fuel-Optimal Electric Propulsion Trajectories**

*Prashant Patel* and Daniel Scheeres*

We discuss our automated algorithm (no initial guess) that can map out the fuel-optimal feasible set including the reachable/controllable set for electric propulsion missions. We provide a detailed discussion of why an indirect multi-stage formulation is well suited to solving this problem over direct and indirect continuous approaches and present an in depth discussion of the theoretical and mathematical underpinnings of our formulation. Reachable and feasible sets for electric propulsion spacecraft are important to many problems.

**08:20 AM**

**129: Design of operational compliant trajectories through a homotopic direct collocation algorithm**

*Alessandra Mannocchi*, Carmine Giordano and Francesco Topputo*

For limited budget reasons, deep-space CubeSats will need to follow operational-compliant trajectories: transfers with thrusting and coasting periods imposed at pre-defined time instants. Traditional trajectory optimisation algorithms exhibit convergence problems when handling discontinuous constraints. In this work, a homotopic direct collocation algorithm mapping the classical bang-bang trajectory of a fuel-optimal low-thrust problem into an operational-compliant solution, is presented. M-ARGO mission is considered as case study for validation, including a realistic thruster model with variable specific impulse and maximum thrust. Our algorithm produces trajectories similar to the optimal solutions without operational constraint, both in terms of thrusting profile and propellant mass.

**08:40 AM**

**207: On the Performance of Different Smoothing Methods for Indirect Low-Thrust Trajectory Optimization**

*Yanis Sidhoum* and Kenshiro Oguri*

This paper compares the performance of two popular smoothing techniques involving the homotopic approach and the hyperbolic tangent smoothing within the indirect formulation of low-thrust minimum-fuel optimization problem in the Restricted Two-Body Problem (R2BP). Their respective performance are investigated on quantitative and qualitative criteria such as computational burden, including number of iterations, convergence time, and accuracy of the optimal solution. Additionally, the Particle Swarm Optimization (PSO) algorithm is used to analyze the global landscape of the performance comparison of the homotopic approach and the hyperbolic tangent approximation. This investigation unifies the available literature and provides useful indications for future low-thrust optimization problems involving bang-bang control inputs.

**09:00 AM** **170: Indirect Forward-Backward Shooting for Low-Thrust Trajectory Optimization in Complex Dynamics**

*Yanis Sidhoum* and Kenshiro Oguri*

An indirect forward-backward shooting method is presented for low-thrust trajectory optimization in complex dynamics with high nonlinearity. The proposed method transforms a Two-Point Boundary Value Problem into a Multi-Point Boundary Value Problem, which is solved by propagating the trajectory forward in time along the first segment and backward in time along the second segment. This approach combines the indirect forward-backward shooting with smoothing technique based on hyperbolic tangent approximation of the bang-bang control inputs. The robustness of this approach allows to solve various transfers in the Earth-Moon circular restricted three-body problem in spite of very simple guess.

**09:20 AM** **263: Solar electric propulsion boosted transfers to the outer solar system**

*Amedeo Rocchi* and Michael Khan*

Transfers to the outer solar system usually rely on multiple inner planet swing-bys to allow mission feasibility. This typically requires a high Earth escape velocity and involves Venus swing-bys, reducing the launch mass and imposing constraints on the spacecraft design. We propose to overcome these drawbacks using solar electric propulsion in the inner solar system to boost the orbital energy. This streamlines the mission profile during the transfer and employs the excess power generated by the large solar arrays with which outer solar system missions are nowadays often equipped. Such transfers are characterized and compared to the conventional multi-swing-bys alternative.

**09:40 AM** **253: Regularized Direct Method for Nonlinear Trajectory Optimization Part 2: Low-Thrust Scenario**

*Kenta Oshima**

The present paper introduces regularized formulations into the direct multiple shooting method of minimizing fuel expenditure for low-thrust spacecraft trajectories. Instantaneous velocity changes approximating low-thrust maneuvers are expressed by regularized variables based on the Levi-Civita or Kustaanheimo-Stiefel transformation. The new formulation removes singularities due to null thrust impulses from derivatives of an objective function and constraints. The method automatically and robustly finds fuel-efficient bang-bang control structures for multi-revolutional transfers between periodic orbits near the Moon without facing the singularities.

# Session: Orbit Determination and Space Surveillance Tracking 1

**Room: Onyx 2-3, Time: 10:20 AM-12:00 PM**

Session Chair: Brandon Jones (The University of Texas at Austin)

**10:40 AM**

**195: Low-complexity algorithms to determine motion in the circular restricted three-body problem**

*David Canales Garcia, Sirani Mututhanthrige Perera, Troy Henderson, Atahan Kurttisi and Brian Baker-McEvilly**

As traffic in the Cislunar region continues to grow, efficient methods to propagate trajectories in the circular restricted three-body problem (CR3BP) are required. Analytical algorithms that are inexpensive and viable for a spacecraft's computational power must be utilized for navigation through the non-linear dynamics of the Earth-Moon system. This investigation develops low-complexity algorithms that may be useful for navigation purposes and tracking relative orbital motion in the three-body problem. Once reliable low-complexity algorithms are determined, they are applied to relevant Cislunar trajectories.

**11:00 AM**

**196: Orbit Determination Design and Analysis for a Single Lunar Swingby Return to GEO Trajectory**

*Marissa Intelisano*, Lisa Policastri and Jill Seubert*

Lunar gravity assists can be used to transfer secondary spacecraft from lunar rideshare launches to near-geosynchronous orbit. Commercial ground station networks offer the tracking services needed to provide tracking measurements for orbit determination and maneuver recovery for such trajectories. This paper summarizes the orbit determination design and analysis performed for a secondary spacecraft utilizing a single lunar swingby trajectory to reach a geosynchronous graveyard orbit. Tracking schedule and maneuver execution assumptions, timelines, goals, methods, and analysis results are discussed.

**11:20 AM**

**211: Optical Tracklet Correlation and Adaptive Birth Modeling for Random Finite Set Filters**

*Steve Gehly*, Marco Langbroek and Brett Carter*

Optical sensors provide an important source of information on objects in Earth orbit, but the resultant short tracklets of angles-only measurements create challenges for orbit determination. Recent work applying a modified version of Gooding's initial orbit determination method to the tracklet correlation problem has achieved excellent computational performance and reliability in associating optical tracklets. This paper adapts and incorporates the method into an adaptive birth process for multitarget filtering suitable for catalog build up and maintenance, demonstrating the method using simulated and real optical measurements from objects across multiple orbit regimes and several nights of observation.

## Session: Orbital Debris and Space Environment

**Room: Topaz 1, Time: 10:20 AM-12:00 PM**

Session Chair: David B. Spencer (The Aerospace Corporation)

**10:20 AM** **279: Image-based Satellite Characterization for Low Earth Orbit**

*Daigo Kobayashi* and Carolin Frueh*

This study proposes a novel approach for characterizing small artificial objects in low Earth orbit (LEO) using compressed sensing on light curve measurements. Light curves are simulated through numerical wave propagation. The light curve model is then adapted into a linear measurement, in which an idea object image is significantly down-sampled by a sensing matrix which is a superposition of point spread functions (PSF map). The object image is recovered using total variation minimization given the light curve and PSF map. The proposed approach demonstrates robustness to imperfect estimates of the PSF map and Poisson noise in the light curve measurement.

**10:40 AM** **384: Uncertainty Analysis of Atlas V Centaur Upper Stage Fragmentation Events**

*Arly Black* and Carolin Frueh*

Fragmentation events threaten the sustainability of space operations,
demanding investigation into the behaviour of debris and their associated uncertainties. This paper advances work begun by Pavi et al. in examinining the break-ups of three Atlas V Centaur upper stages. Three fragmentation object data sources are used in this research. The uncertainty of each fragment is characterized through implementation of an Unscented Kalman Filter, in which a set of deterministically selected sigma points are used to parameterize the mean and covariance of fragment parameters. The validity of the conclusions drawn in the previous work is assessed.

**11:00 AM** **409: Considerations for Space Weather Impacts on Spacecraft**

*Alicia Petersen**

The Sun showers the near-Earth space environment with particles & radiation, and induces geomagnetic storms. These space weather events have damaging effects on spacecraft. Of greatest concern and impact to spacecraft orbiting Earth are energetic particles and space environment changes during geomagnetic storms.
As the space community continues to expand the regimes in which active space exploration and spacecraft operations occur, as when expanding beyond GEO and into cislunar space, the considerations for space weather change. We will discuss these considerations and suggest what proactive measures could be investigated with effective collaboration between the aerospace and space weather research communities.

**11:20 AM** **418: Relative Distance Control of Uncooperative Tethered Debris**

*Liam Field* and Eleonora Botta*

The orbital environment is becoming increasing populated with debris, posing a significant risk to space-based missions. Large debris objects are prime targets for mitigating debris growth. A promising method for the removal of such objects involves an active spacecraft interacting with the debris via a flexible tethered connection. The flexible interconnection poses challenges for mission safety and control, as certain events, such as the tether winding about the target or a possible collision between the objects, can cause catastrophic failure. This work proposes two controllers to prevent such occurrences during the towing phase of the mission.

**11:40 AM** **167: Towards Modeling of RCS Plume Impingement in Space Environments using OpenFOAM**

*Andres Torres-Figueroa, Jonathan Pitt*, Michael Kinzel and Janice Zou*

Unmitigated plume impingement from the Reaction Control System (RCS) engines on approaching spacecraft onto the surfaces of space stations during controlled docking events affectsthe operation life cycle of space stations. While engineering models can provide rapid estimates of the loading and contamination due to RCS plume impingement, high-fidelity simulations are useful for understanding more detailed phenomena and flow interactions. In support of the development of docking control and trajectory design that maximizes station life cycles, this research is focused on presenting the application of existing Direct Simulation Monte Carlo solvers native to the OpenFOAM multi-physics framework for calculating plume impingement effects from rarefied flows in space environments.

**12:00 PM** **173: Modeling of an RCS Thruster Plume to Predict Particle Distribution in Space Environments**

*Janice Zou*, Andres Torres-Figueroa, Michael Kinzel and Jonathan Pitt*

Reaction Control System (RCS) thrusters, when fired during docking, create a scenario involving RCS impingement on the vehicle (self-impingement) and nearby surfaces (space stations). These impingement events are important to control in the trajectory planning of docking to prevent damage. This work fo-cuses on modeling plumes in terms of first principle simulations to improve insight on using computational fluid dynamics (CFD) software as part of planning operations for space applications. The present effort focuses on comparing CFD results of the thruster of interest, the R-4D-11, to existing empirical models.

# Session: Rendezvous, Relative Motion, Proximity Missions, and Formation Flying 1

**Room: Topaz 3, Time: 10:20 AM-12:00 PM**

Session Chair: Siamak Hesar (Kayhan Space Corp)

**10:20 AM** **161: State Transition Tensors for Passive Angles-Only Relative Orbit Determination**

*Jackson Kulik* and Dmitry Savransky*

The passive angles-only initial relative orbit determination problem employs only a camera and no maneuvers of the observing satellite to determining the orbit of another satellite. Under these conditions, linearized dynamics about the observer satellite give rise to an unobservable relative range of the two satellites. We employ the second order state transition tensor about the observer to resolve the range ambiguity, using widely available and efficient linear methods to solve the orbit determination problem. This framework offers good convergence behavior in practice and analytical formulations for the covariance of solutions while being applicable even in three-body formation flying contexts.

**10:40 AM** **112: Periodic Relative Natural Motion in the Circular Restricted Three-Body Problem**

*David Zuehlke*, Alex Sizemore and Troy Henderson*

The problem of finding periodic relative trajectories in the circular restricted three-body problem (CR3BP) is investigated. Closed trajectories in the two-body problem are well known in terms of the Hill Clohessy Wiltshire solutions. A similar framework is sought for the CR3BP wherein natural motion could be utilized to form closed trajectories in the relative frame. Periodic orbit families including HALO, NRHO, Lyapunov, and Axial orbits are investigated for their relative motion properties using a differential corrective process for finding closed relative motion trajectories.

**11:00 AM** **296: Low-Thrust Rendezvous and Proximity Operations in a Near Rectilinear Halo Orbit**

*Carrie Sandel* and Rohan Sood*

With an increasing number of missions planned to cislunar space, on-orbit servicing, inspection, and docking in a multi-body environment will need to take place in non-Keplerian orbits for the first time. Thus, the investigation of these relative motion trajectories is critical to successfully performing rendezvous and proximity operations in cislunar space. In this work, mass and time-optimal trajectories are generated for a low-thrust chaser spacecraft completing a forced loiter sequence about a target on a near rectilinear halo orbit. Constraints on the allowable region for safe rendezvous and proximity operations are applied to investigate the effects on feasible loitering maneuvers.

**11:20 AM** **150: Trajectory Design Considerations for Low Lunar Orbit to Near Rectilinear Halo Orbit Rendezvous**

*Christopher Foster*, Peter Brandt, Marielle Pellegrino, David Strack and cesar ocampo*

NASA's Artemis program plans to use a 9:2 resonant southward Near-Rectilinear Halo Orbit (NRHO) to stage assets for a lunar exploration campaign, including the Gateway space station. While the proximity operations in the NRHO are simple and very similar to flat-space dynamics, the far-field rendezvous has considerations that are non-intuitive, especially to those that may be steeped in the dynamics of rendezvous in Keplerian orbits. We will discuss the key drivers to the delta-V performance of far-field rendezvous from low lunar orbit to the Gateway.

**11:40 AM** **202: Relative Motion on Hyperbolic Atmospheric Entry Trajectories**

*Samuel Albert* and Hanspeter Schaub*

Relative motion about a chief entering the atmosphere from a hyperbolic orbit is considered. State transition matrices or linearized relative equations of motion in terms of orbit element differences that are valid around hyperbolic orbits do exist in the literature. However, these solutions are not necessarily intuitive for the hyperbolic case. To this end, the relative equations of motion are developed and linarized in the velocity frame. This model is then combined with a linearization of the Allen-Eggers analytical solution for steep atmospheric entry, with the aim of approximating relative motion about an entry vehicle.

## Session: Trajectory/Mission/Maneuver Design and Optimization 1

**Room: Topaz 2, Time: 10:20 AM-12:00 PM**

Session Chair: Powtawche Valerino (NASA Marshall Space Flight Center)

**10:20 AM** **204: JUICE Interplanetary Phase: Trajectory Design and Navigation**

*Arnaud Boutonnet*, Yves Langevin and Amedeo Rocchi*

This paper describes the interplanetary transfer of JUICE to Jupiter, which will be launched in April 2023. From a trajectory design point of view, the option is innovative: first it relies on an initial pseudo-resonance, which is surprisingly compatible with Ariane 5 ECA maximum performance close to the equator. Secondly, the transfer features the first Lunar-Earth gravity assist ever flown in history. Finally, a combined deterministic/stochastic optimization led to split the window between two strategies

**10:40 AM** **147: Analysis of DV and eclipse duration for Crank-Over-the-Top and petal rotations in Europa Clipper moon tours**

*Stefano Campagnola*, Etienne Pellegrini, Brian Anderson, Brent Buffington, Try Lam and Ricardo Restrepo*

Crank-over-the-Top and petal rotations are among the most common tour design techniques and have been used on several missions, such as Cassini, Europa Clipper, JUICE. This paper analyzes the $\Delta V$ cost of COTs and petal rotations. While the methods and equations are applied to Europa Clipper, they are also valid for other missions and moon systems. We show that COTs are periodic orbits in the CR3BP, and that the $\Delta V$ in higher fidelity models is caused by the perturbation from Ganymede. Finally, we identify the driving parameters for the eclipse duration and introduce a design strategy to minimize it.

**11:00 AM** **313: Automated Tour Design in the Saturnian System**

*Yuji Takubo*, Damon Landau and Brian Anderson*

Future missions to Enceladus would benefit from multi-moon tours that leverage V-infinity on resonant orbits to progressively transfer between moons. Such "resonance family hopping" trajectories present a vast search space for global optimization due to the different combinations of available resonances and flyby speeds. The proposed multi-objective tour design algorithm optimizes entire moon tours from Titan to Enceladus via grid-based dynamic programming, in which the computation time is significantly reduced by utilizing a database of V-infinity-leveraging transfers. The result unveils a complete trade space of the moon tour design to Enceladus in a tractable computation time and global optimality.

**11:20 AM** **371: A Uranus Mission Design Demonstrating a Simulated Annealing Algorithm**

*Daniel Owen*, Zachary Rhodes and Brian Kaplinger*

The planetary decadal survey has indicated a new interest in missions to Uranus. Traditional mission design methods can be computationally expensive and are not necessarily well suited to the multiple gravity assist problem. This paper proposes a new mission design technique highlighted with a nominal design to satisfy the decadal survey. This new technique utilizes a combination of simulated annealing and genetic algorithms to conduct a trajectory search. Simulated annealing is a relatively new global optimization technique targeted at solving real value problems such as the multiple gravity assist problem. The technique presented is compared against other common techniques and other proposed mission designs in the literature.

**11:40 AM** **282: Double Lunar Swing-by Trajectories to Near-Geostationary Orbit**

*Stephen West*, Mike Loucks and John Carrico*

Lunar and cis-lunar launches create opportunities for orbit transfer vehicles to deliver rideshare payloads to a wide range of final orbits. To enable these transfers, the spacecraft can perform one or more lunar swing-by's to adjust orbital elements without additional propulsive ?V. For rideshare payloads targeting near-geostationary orbits, double lunar swing-by's increase the range of compatible launch targets as compared with single swing-by trajectories. We developed a set of double-lunar swing-by transfers from a direct lunar launch to near-geostationary orbit and compared them with analogous single swing-by trajectories over the same launch period.

# Session: Asteroid and Small Body Missions

## Room: Topaz 3, Time: 01:30 PM-03:10 PM

Session Chair: Paul Thompson (Emergent Space Technologies)

**01:30 PM**

**126: Small Body Navigation and Gravity Estimation using Kalman Filter and Least-Squares Fitting**

*Julio C. Sanchez* and Hanspeter Schaub*

This paper considers the problem of joint state and gravity estimation around a small body. For this purpose, an unscented Kalman filter is combined with a leastsquares fitting of the spherical harmonics coefficients. These are inferred by using the filter position and perturbing acceleration estimates. The available measurements are assumed to be pixels locations of surface landmarks. Three setups with different needs of batch data processing are analyzed. These are compared in terms of accuracy, computational efficiency and memory requirements through numerical simulations.

**01:50 PM**

**297: Simultaneous Optimization of Guidance and Navigation Accuracy for Small Body Terminal Approach Trajectory Design**

*Yuichi Tsuda*, Yusuke Oki and Shota Kikuchi*

This paper describes a methodology to design terminal approach trajectory to small bodies with large ephemeris uncertainty. we consider a terminal approach trajectory optimization which can explicitly include the ephemeris uncertainty and can systematically constrain the stochastic dispersion of the total required fuel. This method minimizes the sum of the deterministic and stochastic delta-V while the final state at the small-body arrival can be arbitrarily constrained. The resulting technique was applied to the terminal approach phase of the Japanese asteroid explorer Hayabusa2 to reach asteroid Ryugu, successfully constraining uncertainties in the final state and the stochastic delta-V simultanelously.

**02:10 PM**

**302: Improvement to Hera Orbit Determination and Gravity Science via inclusion of LIDAR measurements**

*Edoardo Gramigna*, Riccardo Lasagni Manghi, Marco Zannoni, Paolo Tortora, Nicole Dias, Paulo Gordo and Rui Melicio*

We present our orbit determination simulations of the radio science experiments with ESA’s Hera mission in the context of gravity science investigations. In particular, we focus on the role of the PALT LIDAR experiment measurements which, combined with radiometric and optical navigation images, allow us to better estimate the scientific parameters of interest. Preliminary results confirm that the LIDAR measurements allow constraining Hera’s trajectory, which results in a better estimation of several parameters as Dimorphos’ orbit, and the mass, mass distribution and gravity field of the Didymos binary system.

**02:30 PM** **305: Radio Science Investigations for the Heavy-Metal Mission to Asteroid (216) Kleopatra**

*Paolo Tortora, Riccardo Lasagni Manghi*, Edoardo Gramigna, Marco Zannoni, Jan-Erik Wahlund and Jan Bergman*

This work presents the simulation results of the radio science experiment onboard the proposed Heavy Metal mission to the M-type asteroid (216) Kleopatra. Radiometric measurements from ground-based tracking link and from the intersatellite link between the primary and secondary spacecraft are used in an orbit determination process to assess the attainable formal uncertainty for the gravity parameters of interest. Preliminary results indicate that the asteroid mass and gravitational field can be estimated with very good accuracy to meet the scientific goals of the mission.

**02:50 PM** **317: Navigating a Dual-Spacecraft Bistatic Radar Around an Asteroid**

*Andrew French*, Yu Takahashi, Rodney L. Anderson, Shyam Bhaskaran, Saptarshi Bandyopadhyay and Rashied Amini*

DROID, a low-cost mission concept being proposed by NASA JPL and CNES, is a multi-spacecraft mission to the potentially hazardous asteroid 99942 Apophis. The mission system consists of a Mothership and two 6U CubeSats, where the pair of CubeSats form a multistatic radar system designed to measure the internal structure of Apophis. To facilitate these measurements, the two CubeSats must be navigated with sufficient accuracy to maintain a near-antipodal orbital configuration at a low altitude. In this paper we present navigation analysis that is being used to drive mission requirements.

## Session: Dynamical Systems Theory Applied to Space Flight

**Room: Topaz 1, Time: 01:30 PM-03:10 PM**

Session Chair: David Canales Garcia (Embry-Riddle Aeronautical University)

**01:30 PM** **105: Method to Target Quasi-Periodic Orbit Frequencies Within Multi-Parameter Families**

*David Lujan* and Daniel Scheeres*

Studies utilizing methods to compute families of quasi-periodic orbits (QPOs) don't focus on the computation of specific family members, but instead are used to research entire families of orbits. An algorithm is proposed to target the frequencies of a QPO lying inside a multi-parameter family. This method makes use of the tangent space of QPOs to construct a family tangent vector to control the continuation procedure to move toward an orbit with a desired set of frequencies. Additionally, a new method of picking step sizes is introduced which picks a step size within an interval to predict the next QPO in the continuation to have the most incommensurate frequencies.

**01:50 PM** **178: Restricting Spacecraft Uncertainty Evolution With Modified Hamiltonian Constraints In Non-Conservative Systems**

*Oliver Boodram* and Daniel Scheeres*

Structures are constrained to preserve geometric and probabilistic properties as they evolve in phase space under Hamiltonian dynamics. These structures can represent some uncertainty region where the spacecraft state is likely to reside. Spacecraft uncertainty is then subject to these constraints which can provide insight into state determination. This work derived the modified constraints in the presence of non-conservative forces. The modified constraints were then verified in an atmospheric drag environment. From these modified constraints, we were able to present a coupling in spacecraft coordinate uncertainty and knowledge gained regarding the future state of the spacecraft.

**02:10 PM** **229: Low Thrust Augmentation for Ballistic Lunar Transfers**

*Stephen Scheuerle*, Kathleen C. Howell and Diane Davis*

Low-energy transfers offer fuel-efficient paths to the Moon. This investigation introduces techniques for constructing low-energy lunar transfers with a focus on the trade-offs between time-of-flight and propellant requirements, if any. A type of low-energy transfer, denoted as Ballistic Lunar Transfer (BLT), leverages the gravitational influence of the Sun to reduce the propellant cost upon arrival into orbits near the vicinity of the Moon. To model a spacecraft governed by the Earth-Moon-Sun system, the Bicircular Restricted Four-Body Problem (BCR4BP) is incorporated. To explore the range of possible transfer geometries, impulsive maneuvers and low-thrust transfer arcs are considered.

**02:30 PM** **230: Toward Immersive Spacecraft Trajectory Design: Mapping Arbitrary Drawings to Natural CR3BP Periodic Orbits**

*Dhathri Harsha Somavarapu and Davide Guzzetti**

Immersive technology may offer novel user interaction modalities to manipulate and design spacecraft trajectories within complex dynamical environments. This paper presents an investigation into mapping arbitrary curves drawn by a human user within a three-dimensional canvas to the natural circular restricted three-body (CR3BP) periodic orbits. We pose a "Drawing-to-CR3BP-Orbit-Mapping" problem and propose a solution for it. We employ a collocation optimizer connected to a virtual reality application to explore solutions for a given arbitrary human drawing. We present baseline results obtained for {Lyapunov, halo, axial and vertical} drawings from our setup. The results are promising in terms of recovering corresponding orbits of the intended shape of the human drawing.

**02:50 PM** **422: Computation of Quasi-periodic Orbits in the Zonal Harmonics Problem**

*Julia Pasiecznik*, Celina Pasiecznik, Miles Lifson and Richard Linares*

This work computes quasi-periodic orbits in the zonal harmonics problem of artificial satellite theory and studies their implications on orbital capacity for satellite constellations in low Earth orbit (LEO). The design of quasi-periodic orbits that enable close concentric stacking of orbital shells, particularly in the presence of perturbations, enables increased orbital capacity. We study the disturbances to quasi-periodic orbits made by adding higher-order perturbations from the oblateness of the Earth from a dynamics perspective and their implications on satellite constellations in LEO.

## Session: Spacecraft Guidance, Navigation and Control 1

**Room: Topaz 2, Time: 01:30 PM-03:10 PM**

Session Chair: Angela Bowes (NASA LaRC)

**01:30 PM**

**103: Pre-Launch Electric Propulsion Error Models for Psyche Navigation**

*Nicholas Bradley*, Steve Snyder, Daniel Lubey, Alex Manka, Drew Jones, Dayung Koh and Dianna Velez*

The Psyche mission is planned to travel to the main belt asteroid (16) Psyche, and will use Hall Effect thrusters for all deterministic thrusting. We present a substantive update to the navigation uncertainty model for the mission's electric propulsion thrusting, greatly refining error models presented in a previous publication. The new models are based on recent laboratory test data and extensive analysis of the spacecraft agility capabilities. Error models for both thrust magnitude and direction are presented, followed by a discussion of navigation filter setup for pre-flight covariance studies and in-flight reconstruction of electric propulsion related parameters.

**01:50 PM**

**117: High-Order Guidance for Time-Optimal Low-Thrust Trajectories with Automatic Domain Splitting**

*Adam Evans, Roberto Armellin*, Laura Pirovano and Nicola Baresi*

This paper develops a high-order guidance scheme based on the expansion of the solution of a time-optimal low-thrust optimal control problem. New optimal trajectories can be computed by the simple evaluation of polynomials, including updated time-of-flights. A technique known as automatic domain splitting is implemented to further improve the guidance scheme by adaptively and automatically splitting the uncertainty domain into smaller subdomains, generating new guidance polynomials which are better equipped to handle deviations in their respective subdomains. By tracking the approximation error and splitting accordingly, the control and time-of-flight updates are provided to a specified accuracy, a significant advantage over previous differential algebra guidance schemes.

**02:10 PM**

**146: Solar Sailing Adaptive Control Using Integral Concurrent Learning for Solar Flux Estimation**

*Luis Mendoza Zambrano* and Riccardo Bevilacqua*

In the interest of exploiting natural forces for propellant-less spacecraft missions, this investigation proposes an adaptive control strategy to account for unknown parameters in the dynamic modeling of a reflectivity-controlled solar sail spacecraft. A Lyapunov-based control law along with integral concurrent learning is suggested to accomplish and prove global exponential tracking of the estimated parameters and the state without the common persistence of excitation condition. This involves estimating the solar flux or irradiance from the Sun to account for uncertainty and variation over time in this value.

**02:30 PM**

**186: Combined Convex and Direct Shooting Optimization for Low-Thrust Trajectory Generation With Analytical Thrust Profile**

*Andrea Carlo Morelli*, Alessandro Morselli, Carmine Giordano and Francesco Topputo*

Convex optimization for low-thrust trajectory generation guarantees high levels of robustness with low computational time. However, it is affected by one disadvantage: constraints are only respected at the discretization points. Outside of these points, physical constraints on the thrust vector might therefore be violated. Consequently, the output of the algorithm could not be used directly for future autonomous guidance scenarios. We develop an algorithm that exploits convex optimization to find a solution to the low-thrust trajectory optimization problem and transforms its control output into a perfectly bang-bang thrust profile where the thrust angles are expressed analytically using arbitrary-order polynomials.

**02:50 PM**

**264: Controllability of satellites on periodic orbits with cone-constraints on the thrust direction**

*Alesia Herasimenka*, Lamberto Dell'Elce and Ariadna Farres*

Many observation satellites are subject to attitude constrains arising from peculiar mission requirements or environmental conditions. These obstructions often con- strain the direction of the thrust vector to remain within a cone. In this study, we investigate the local controllability of station-keeping maneuvers of satellites with low thrust capabilities or small chemical impulsions on nominal periodic orbits subject to such constraints. We offer a numerical methodology based on convex optimization to identify the minimum cone angle guaranteeing local controllabil- ity for a specific orbit. An illustrative example inspired by the James Webb Space Telescope is proposed. Specifically, we consider a satellite on a Halo orbit around L2 in the Sun-Earth system.

## Session: Trajectory/Mission/Maneuver Design and Optimization 2

### Room: Onyx 2-3, Time: 01:30 PM-03:10 PM

Session Chair: Jin Haeng Choi (Yonsei University)

**01:30 PM**

**220: State-dependent trust region for successive convex optimization of spacecraft trajectories**

*Nicolò Bernardini*, Minduli Charithma Wijayatunga, Nicola Baresi and Roberto Armellin*

Successive convex programming is a promising technique for on-board applications thanks to its speed and guaranteed  onvergence and it can be an enabler for future missions where spacecraft autonomy plays a key role. The definition of a good value of the trust region plays an key role in the convercence of SCVX algorithms. This work presents an improved trust region based on differential algebra technique which relies on the information given by the non-linearities of the constraints and does no depend on the user initialization of the trust region.

**01:50 PM** **108: Sequential Quadratic Programming for Spacecraft Trajectory Optimization using Nested Differential Correctors**

*Alfred Lynam**

DME Component Libraries is a standalone aerospace software library that is distinct from AGI's flagship product STK, but contains an important subset of STK's functionality. This paper highlights the recent incorporation of an active set SQP (Sequential Quadratic Programming) optimizer into DME Component Libraries. This optimizer is capable of solving spacecraft trajectory optimization problems with a cost function and multiple equality or inequality constraints. However, testing has shown that the optimizer performs better when equality constraints are handled using nested differential correctors, which are also available in DME Component Libraries.

**02:10 PM** **138: Regularized Direct Method for Nonlinear Trajectory Optimization Part 1: High-Thrust Scenario**

*Kenta Oshima**

This paper develops a regularized formulation in the fuel minimization problem for impulsive spacecraft trajectories. The method introduces regularized variables based on the Levi-Civita or Kustaanheimo-Stiefel transformation into the direct multiple shooting procedure to express instantaneous velocity changes. The new formulation removes the notorious singularities due to null thrust impulses from derivatives of an objective function. The favorite singularity-free property enables accurate reductions of unnecessary impulses and additions of necessary impulses for local optimal solutions in an automatic manner. The method is applied to several test cases for demonstrating its effectiveness.

**02:30 PM** **165: Structure Detection Method for Solving State Variable Inequality Path Constrained Optimal Control Problems**

*Cale Byczkowski* and Anil Rao*

A structure detection method is developed for solving state-variable inequality path constrained optimal control problems. The method obtains estimates of activation and deactivation times of active state-variable inequality path constraints (SVICs), and subsequently allows for the times to be included as decision variables in the optimization process. Once the identification step is completed, the method decomposes the problem into a multiple-domain formulation consisting of constrained and unconstrained domains. Within each domain, Legendre-Gauss-Radau (LGR) orthogonal direct collocation is used to transcribe the infinite-dimensional optimal control problem into a finite-dimensional nonlinear programming (NLP) problem. The accuracy of the proposed method is demonstrated on a well-known optimal control problem which contains a SVIC.

**02:50 PM**

**324: Distributed Swarm Optimization for the Solution of Boundary Value Problems in Astrodynamics**

*Grant Hecht*, Eleonora Botta and Nick Furioso*

A distributed computing framework based on a novel multi-swarm particle swarm optimization algorithm is proposed for computing the solutions of Two-Point Boundary-Value Problems (TPBVP)s in astrodynamics employing High-Performance Computing (HPC) architectures. The proposed methodology is applied to compute solutions of two unique TPBVPs: the first involving the optimal transfer of a spacecraft employing the indirect approach, and the second for computation of periodic trajectories in the circular restricted three-body problem. The proposed methodology is shown to facilitate the rapid discovery of multiple solutions to each problem without the need for a user-provided guess, an advantageous feature for the preliminary phase of mission design.

## Session: Asteroid and Small Body Missions

### Room: Topaz 3, Time: 03:30 PM-04:50 PM

Session Chair: Paul Thompson (Emergent Space Technologies)

**03:30 PM**

**330: Rigid-Body Spacecraft Dynamics Analysis in a Binary System Using Formulation in Lie Groups**

*Brennan McCann*, Annika Anderson, Morad Nazari and David Canales Garcia*

A compact formalism on the special Euclidean group SE(3) is employed for the analysis of rigid-body spacecraft motion in a binary system. The circular restricted full three body problem (CRF3BP) is studied, where the mass distributions of all bodies, including the spacecraft, are considered. The orbit/attitude coupling due to the gravitational moments and forces for the CRF3BP problem is presented. Equilibrium solutions and zero velocity curves are presented. Then, the dynamics of spacecraft are compared with those considering a point-mass model for the spacecraft in this problem. Numerical simulations are provided on a binary system.

**03:50 PM**

**374: Maneuver strategy optimization of the approach phase in an asteroid rendezvous mission**

*William Wang*, James Liu and Zhong-Sheng Wang*

Near the end of the Earth-to-asteroid transfer in an asteroid rendezvous mission, an approach phase is arranged so that an asteroid capture maneuver with large delta-V can be replaced by several maneuvers with smaller delta-Vs. The error in relative position at the aim point is quite large when a maneuver strategy of the approach phase is employed based on the probe orbit determination from the ground stations and the asteroid ephemeris propagation. If the relative navigation based on optical measurements is introduced in optimizing the maneuver strategy, the error in relative position at the aim point can be significantly reduced.

**04:10 PM** **140: Interstellar Object Uncertainty Evolution and Effect on Fast Flyby Delivery and Required Delta-V**

*Declan Mages*, Davide Farnocchia and Benjaman Donitz*

With the discovery of 1I/'Oumuamua and 2I/Borisov, interstellar objects (ISOs) have been thrust into the forefront of planetary science. A promising near term mission concept to explore these objects is a rapid responce fast flyby/impact spacecraft. However ISO hyperbolic orbits result in high relative velocity encounters and high solar phase angles, while short astrometric observation arc lengths produce large ephemeris uncertainties that can change dramatically during cruise. This work demonstrates how these two challenges can lead to hundreds of meters per second of required statistical delta-v for navigation, reduce human in the loop delivery accuracy to hundreds of kilometers, and likely require autonomous guidance.

## Session: Dynamical Systems Theory Applied to Space Flight

### Room: Topaz 1, Time: 03:30 PM-04:50 PM

Session Chair: David Canales Garcia (Embry-Riddle Aeronautical University)

**03:30 PM** **276: Detecting Heteroclinic Connections Between Quasi-periodic Invariant Tori Using Knot Theory**

*Danny Owen* and Nicola Baresi*

Methods of generating heteroclinic connections between quasi-periodic orbits typically rely on human-in-the-loop or machine learning techniques to find intersections in sets of data in more than three dimensions. We propose a fully systematic method of generating these connections using an invariant property found in knot theory: the linking number. This method proves to be robust in generating heteroclinic connections between isoenergetic invariant tori in the circular restricted three-body problem.

**03:50 PM** **354: Exploration of Transfer Opportunities to Low Lunar Orbits in the Cislunar Framework**

*Mackenzie Mangette* and Roshan Thomas Eapen*

The cislunar libration point orbits and lunar orbits have important strategic value as potential staging locations for missions to the lunar surface and into deep space. This study will explore transfers from cislunar Halo orbits to Low Lunar Orbits. Departure locations are selected on the 9:2-resonant southern Near Rectilinear Halo Orbit, which is the proposed orbit for the Lunar Gateway. Two-parameter families of transfers are introduced and described by characteristic surfaces in the transfer space. The $\Delta v$ map to quantify transfer costs to access any reference lunar site described by longitude and latitude is also presented.

**04:10 PM**

**318: A hybrid stochastic-deterministic integrator for spacecraft dynamics with uncertainty**

*Carmine Giordano* and Francesco Topputo*

High-fidelity spacecraft trajectory propagation can become a cumbersome task when dealing with uncertainties modeled as random processes. The stochastic differential equations describing the uncertain dynamics can be numerically integrated, but they are challenging from the computational point of view. Traditional methods usually require either the storage of a relevant amount of data or small integration steps. In this work, an hybrid method, embedding a stochastic integration method in a deterministic higher-order scheme, is conceived to obtain fast and stochastically correct results. Results show a reduction of at least one order of magnitude for both computational time and memory usage with respect to state-of-the-art techniques, while it is able to provide

**04:30 PM**

**130: Tracing Position in the Regime of the Restricted Three-Body Problem to a Halo Orbit**

*Hailee Hettrick*, Begum Cannataro and David Miller*

A methodology is developed that exploits the approximate, analytical closed-form solutions of the circular restricted three-body problem via the Lindstedt-Poincaré method to determine the periodic orbit -- and the position along that periodic orbit, denoted by the time in orbit -- that a point in space in the vicinity of a Lagrange point belongs. The Lindstedt-Poincaré solutions allow for partial inverse functions of the characteristic time and amplitude associated with a position to be evaluated. This methodology enables a new avenue for trajectory design in the restricted three-body problem.

## Session: Spacecraft Guidance, Navigation and Control 1

**Room: Onyx 2-3, Time: 03:30 PM-04:50 PM**

Session Chair: Angela Bowes (NASA LaRC)

**03:30 PM**

**136: Fast Model Predictive Control for Spacecraft Rendezvous and Docking with Obstacle Avoidance**

*Courtney Bashnick* and Steve Ulrich*

This paper develops a Fast Model Predictive Control guidance algorithm for autonomous spacecraft rendezvous and docking. Specifically, the algorithm produces fuel-optimal collision-free trajectories by solving a convex optimal control problem using a gradient-based method called the infeasible start Newton method. The convex obstacle avoidance constraints are formulated using a direct linearization approach. Two- and three-dimensional simulations demonstrate the superior optimality and speed of the solver compared to commercially available solvers. The guidance algorithm is executed on an air-bearing testbed to demonstrate its real-time implementability and shows excellent agreement with simulated results.

03:50 PM

**239: Autonomous and Resilient Orbit Estimation Technique Using Lunar Reflectors**

*Jared Frank* and Ahmad Bani Younes*

This paper investigates the practicality of an autonomous and resilient positional navigation using corner cube reflectors on the lunar surface. The proposed approach stands as an efficient navigation solution when the current system, e.g. GPS is being attacked, jammed or spoofed by a third party. The paper provides a complete setup of the mathematical models using a nonlinear least squares algorithm. Numerical simulations are presented to show the accuracy, performance and practicality of the proposed solution.

04:10 PM

**244: Higher Order Control Lyapunov-Barrier Functions for Real-Time Optimal Control of Constrained Non Affine Six-Degree-of-Freedom Powered Descent**

*Alaa Eddine Chriat* and Chuangchuang Sun*

This paper presents a synthesis of higher order control Lyapunov functions (HOCLF) and higher order control barrier functions (HOCBF) capable of controlling non-linear dynamic systems while maintaining safety.we propose a HOCLF form that ensures convergence of coupled dynamics to target states. We combine the HOCLF with HOCBF to guarantee safety. This online optimal control problem is then formulated as a CONVEX Quadratic Program (QP). Lastly, we propose a heuristic approach to ensure the feasibility of the QPs. The efficacy of the suggested algorithm is demonstrated on the real-time six-degree-of-freedom powered descent optimal control problem.

## Session: Trajectory/Mission/Maneuver Design and Optimization 2

**Room: Topaz 2, Time: 03:30 PM-04:50 PM**

Session Chair: Jin Haeng Choi (Yonsei University)

03:30 PM

**261: A GEOMETRICAL ANALYSIS OF TWO-IMPULSE TRANSFERS BETWEEN LISSAJOUS ORBITS**

*Takuto Shimazaki* and Yasuhiro Kawakatsu*

Two-impulse transfers between Lissajous orbits in the circular restricted three-body problem are analyzed based on the linear structure of the phase space near the libration points. Using a geometrical classification of linear solutions, transfer trajectories are categorized into two major types of transfers, which are then formulated as two successive single-impulse transfer problems and a two-point boundary problem. The feasible solutions of both types of transfer problems are extensively analyzed, and the cost of transfer is evaluated. The presented results provide insight into the dynamics of impulsive transfers near a libration point and can serve as reference trajectories for optimizations.

**03:50 PM** **243: Optimization of the Two Impulse Orbit Transfer**

*Grant Hevia**

An analytical method of optimizing the Keplerian time free two impulse orbital transfer problem will be presented. Finding the optimal transfer requires optimal transfer geometry between points on the orbits and optimal points from which to transfer. To accomplish this, the orbit transfer will be optimized over the semilatus rectum of the transfer arc as well as the true anomalies of the initial and final orbits. Solutions will be presented for singularity cases as well. The methods will be evaluated using example orbits, and porkchop plots will be used to and validate that the trajectory is optimal.

**04:10 PM** **254: Efficient Numerical Solution of the Low-Thrust Lambert Problem**

*Lamberto Dell'Elce*, Alesia Herasimenka, Nicola Baresi and Aaron Rosengren*

An algorithm for the numerical solution of low-thrust Lambert's problem is proposed. After averaging the extremal flow of the optimal control Hamiltonian, a one-parameter family of solutions of a reduced-order two-point boundary value problems is achieved by means of a differential continuation scheme. Sensitivities of the shooting function are then used in conjunction with an ad hoc near-identity transformation between averaged and osculating variables to achieve an accurate solution for all longitudes of the departure and arrival orbits. Hence, a single simplified shooting problem has to be solved to approximate the solution for any combination of departure and arrival dates (\textit{i.e.}, to draw a pork chop chart).

**04:30 PM** **307: Existence of Infinitely Many Optimal Equal-Delta-v Trajectories in Two-Body Dynamics**

*Keziban Saloglu*, Ehsan Taheri and Damon Landau*

We study the multiplicity of minimum-delta-v impulsive trajectories for long-time-horizon problems. One notable feature of these extremal impulsive trajectories is that many of the impulses are applied at a specific position, highlighting the significance of what we coin as ``impulse anchor positions.'' We demonstrate that for long-time-horizon maneuvers and under the inverse-square gravity model, all multiple-impulse, minimum-delta-v solutions can be generated using a phase-free two-impulse baseline solution. We propose a fast method to generate multiple-impulse minimum-delta-v trajectories by forming algebraic delta-v allocation problems. We recover all families of impulsive solutions for a benchmark problem, and we classify the solutions to show that there are infinitely many optimal equal-delta-v solutions.

# Tuesday, January 17

## Session: Cislunar Space Missions and Operations 1

**Room: Onyx 2-3, Time: 08:00 AM-10:00 AM**

Session Chair: Diane Davis (NASA Johnson Space Center)

**08:00 AM** **119: Touring Cislunar Periodic Orbit Test Case for Earth-Moon Search and Rescue**

*Adam Wilmer*, Robert Bettinger and Thomas Fay*

Th is work investigates and analyzes a search and rescue mission comprising a spacecraft in a touring cislunar periodic orbit (TCPO) that will rendezvous with an impaired spacecraft in an near-rectilinear halo orbit (NRHO) about the L2 Lagrange point. This work will simulate a variety of rendezvous' in which both the impaired spacecraft's and the rescuer spacecraft locations are varied. Psuedospectral methods within the circular restricted three-body problem (CR3BP) are utilized to find optimized least time solutions given a max $\Delta V$. The results of this work show the TCPO used in this work to be advantageous in timely rendezvous with an impaired spacecraft in a NRHO.

**08:20 AM** **120: Optimal Low Thrust Trajectory from NRHO to LLO using High-Fidelity Dynamics**

*Joshua Fofrich*, Alex Pascarella and Robyn Woollands*

This paper describes the methodology and results that were obtained for computing a low-thrust, minimum-fuel, trajectory from a highly eccentric Near Rectilinear Halo Orbit in the Earth-Moon system at L2 to a highly inclined low Lunar orbit. The trajectory optimization is formulated using an indirect optimization method and Modified Equinoctial Elements. The simulated dynamics includes a 3x3 degree and order spherical harmonic gravity model for the Moon and third-body perturbations from the Earth and Sun, along with solar radiation pressure. We show a candidate transfer trajectory solution that reaches the LLO with an altitude of 100 km, from the NRHO.

**08:40 AM** **123: Preliminary Study of Utilizing Electric Propulsion for Rendezvous Operations with Example Cislunar Periodic Orbits**

*Adam Wilmer*, Robert Jones, Robert Bettinger and Costantinos Zagaris*

The past decade has witnessed a growth in international attention placed on investigating cislunar mission operations. With this increased attention, methods for an effective source of propulsion for low-thrust maneuvers along these orbits must be investigated. This research aims to compare the propellant required to effectively rendezvous with a target spacecraft in different sections of its cislunar periodic orbit. The target is assumed to be in need of re-servicing, and electric propulsion is investigated as a potential means to save on propellant when performing rendezvous maneuvers. The results of this work show electric propulsion to be effective at rendezvousing with various locations in the same TCPO when response time is not critical.

**09:00 AM**

**162: Sensitivity to Navigation and Operational Errors for Earth Escape Trajectories via Multiple Lunar Flybys**

*Ricardo Lozano Ortega*, Joan-Pau Sanchez and Antonio Checa Cañadas*

This paper revises the state-of-the-art of Earth-Moon ballistic escape trajectories via multiple lunar flybys. It presents a sensitivity analysis to navigation and propulsion errors of an escape trajectory. It is proved the existance of an escape trajectory capable of reaching hyperbolic escape velocities of up to 1.5 km/s using two Moon gravity assists and one deep space manoeuvre lower than 100 m/s in less than 90 days. The main contribution of this work is a deeper understanding of the most critical parameters and events in the navigation, propulsion and trajectory design, along with the expected escape accuracy.

**09:20 AM**

**194: A review on hot-spot areas within the Cislunar region and upon the Moon surface, and methods to gather passive information from these regions**

*Brian Baker-McEvilly*, Sebastian Doroba, Annika Gilliam, Franco Criscola, David Canales Garcia, Carolin Frueh and Troy Henderson*

The Cislunar region is becoming a focal point of expansion over upcoming decades. Long-term Lunar infrastructure supporting Cislunar expansion must be located in key regions on the Moon's surface and in space. The purpose of this paper is to identify key regions of interest on and around the Moon by investigating the location of valuable resources and the destination of future missions. Once key regions are established, methods to gain passive information are studied to service determined regions of interest.

**09:40 AM**

**201: Thrust dispersion analysis for direct phasing strategies with Earth-Moon L2 Near Rectilinear Halo Orbits**

*Giordana Bucchioni*, Paolo Guardabasso, Stéphanie Lizy-Destrez, Léa Rouverand and Mario Innocenti*

In light of the renewed interest in Moon exploration, the paper presents a thrust dispersion analysis for direct phasing manoeuvres with a Near Rectilinear Halo Orbit around the Lagrangian point L2 in the Earth-Moon system.
The scope of the work is to present a bi-impulsive, direct phasing manoeuvre between a passive target and an active chaser and to asses its robustness with respect to perturbation in thrust amplitude and direction, in the perspective of future mission design.

## Session: Earth Orbital Missions and Studies

### Room: Topaz 1, Time: 08:00 AM-10:00 AM

Session Chair: Arnaud Boutonnet (European Space Agency / ESOC)

**08:00 AM**

**380: Application of Theory of Geographically Correlated Orbit Perturbations to Space Geodetic Analysis**

*Benjamin Krichman*, Srinivas Bettadpur and Nicholas Childress*

For space-based measurements of geophysical processes which are dynamically linked to the orbit of the measurement platform, the Theory of Geographically Correlated Orbit Perturbations (TGCOP) provides a mathematical framework for separating out orbit perturbations that arise specifically from the nature of the quantity being measured. The TGCOP has been utilized in characterization and analysis of error in the time-variable gravity field solutions produced by the GRACE and GRACE-FO missions. Its application has led to improvements in background de-aliasing gravity models, localization of gravity field signals not fully captured in the measurements, and effective diagnostic tools for improvement of orbit determination.

**08:20 AM**

**153: Conceptual Design for Returning KITSAT-1**

*Yehyun Kim*, Taejin Chung, Son-Goo Kim and Sejin Kwon*

Due to the increase in the number of satellites, Active Debris Removal and On-orbit Servicing missions get spotlighted. Therefore, KAIST Satellite Technology Research Center planned to capture and de-orbit Korea's first satellite, KITSAT-1, as one of the Active Debris Removal missions. For the success of the project, mission planning for orbit transfer and rendezvous would be considered under fuel optimization. In this research, we designed the trajectory that could capture KITSAT-1 conceptually by considering the optimized fuel.

**08:40 AM**

**311: Enabling Space-Based Computed Cloud Tomography with a Mixed Integer Linear Programming Scheduler**

*David Stanley*, Amir Rahmani, Robyn Woollands, Federico Rossi and Changrak Choi*

Conventional remote cloud observation methods are inadequate for inferring the internal structures of low convective clouds. Cloud tomography is able to reconstruct these clouds by imaging a single cloud target from multiple locations with a large angular range. Many low convective clouds only have a lifetime of 15-25 minutes necessitating autonomous scheduling of observation targets as they appear. Mixed integer linear programming can solve for an optimal observation schedule in a maximum time of 15 ms on a conventional desktop CPU. The MILP scheduler is able to observe 59.4% more targets than a conventional push broom camera configuration.

09:00 AM

**383: An approach to optimal orbit design with a novel technique for the revisit and coverage estimation for a Very Low Earth Orbit Earth Observation Mission**

*Kavya Karampuri* and Akash Yalagach*

To cater to the rising demand for hi-resolution satellite Imagery, satellites are being launched into Very Low Earth Orbits (VLEO) and Low Earth Orbits (LEO). This paper discusses an approach to optimal orbit design using a heuristic optimization technique and an iterative method to arrive at the best altitude for an EO VLEO mission. A novel technique involving an effective J2 propagation model is proposed to estimate the revisit and coverage metrics for different sensor footprints, involving nadir and off-nadir scenarios. Also, a coverage plan is proposed to predict the best case maximum area coverage opportunities in a minimum timeframe.

## Session: Rendezvous, Relative Motion, Proximity Missions, and Formation Flying 2

### Room: Topaz 3, Time: 08:00 AM-10:00 AM

Session Chair: Robert Melton (Pennsylvania State University)

08:00 AM

**113: Regions of Application for Linearized Relative Motion in the Restricted Three Body Problem**

*David Zuehlke*, Alex Sizemore and Troy Henderson*

Increased interest in cislunar space prompts the study of relative dynamics in this domain. Previous work developed a set of linearized equation of motion (EOMs) for the ER3BP. Investigation is performed to determine orbit families and time-spans of applicability for the linearized equations and their corresponding matrix exponential solution. Orbits investigated for relative motion error include earth-orbiting for verification, low-lunar, and HALO orbit families. Analytical considerations are performed as well as Monte-Carlo simulations to determine when the EOMs are valid. Natural motion only is considered for this research.

08:20 AM

**323: Relative Motion For Non-Keplerian Dynamics Using Interpolated State Transition Tensors**

*David Cunningham* and Ryan Russell*

The problem of relative motion modeling between a target spacecraft and a chaser spacecraft when the target's motion has no analytic solution is relevant for many future space missions. This paper investigates a family of methods for non-Keplerian relative motion modeling based on interpolation of the first and second variations of the target's trajectory (state transition matrix/tensor). Using the Gateway as a case study, we evaluate different interpolation methods. The interpolated models are characterized in terms of accuracy, speed, and memory requirements, including comparison against reference models representing current state of practice.

**08:40 AM** **367: Analysis of Relative Motion Trajectories in the Circular Restricted Three-Body Problem**

*Michael Mercurio*, Christopher Roscoe and Jason Westphal*

Spacecraft formations are a key enabling technology in space mission design. Formations are often selected to meet complex mission requirements otherwise unattainable by a single spacecraft. The existence of closed-form analytical expressions resulting from the Hill-Clohessy-Wiltshire equations provide mission planners with tools to quickly design specific formation parameters. No such expressions exist for parameters of relative trajectories in cislunar space. This paper presents an overview of techniques for analyzing and designing relative trajectories in the Circular Restricted Three-Body problem, focusing on a modal-based solution developed from Lyapunov-Floquet theory.

**09:00 AM** **381: Inverse-Optimal, Continuous-Thrust Orbit Transfers**

*Ahmed Atallah* and Ahmad Bani Younes*

We present an approach for constructing optimal feedback control laws for continuous-thrust orbit transfers between elliptic Keplerian orbits. The inverse optimal approach is employed to avoid solving a Hamilton Jacobi equation, resulting in an optimal controller with respect to a meaningful cost functional. In this paper, the cost functional is a function of gains to be tuned by the user. A good choice of these gains may result in nearly time- or fuel-optimal trajectories. Therefore, one application of the inverse-optimal control investigated in this paper is to provide a good initial guess when designing optimal open-loop trajectories.

**09:20 AM** **214: Numerical Optimization Study of Spacecraft Rendezvous Using Nonlinear Relative Motion**

*Ireland Brown* and Anil Rao*

A numerical optimization study of spacecraft rendezvous is performed. Two-body inverse-square gravitation is used to model the motion of both the target and chaser vehicles, and it is assumed that the target vehicle is in a circular orbit. In addition, the chaser is subject to thrust. The following four optimal control problems are then formulated for steering the chaser to the target: (1) minimum-fuel with fixed terminal time; (2) minimum-fuel with free terminal time; (3) minimum-time with fixed fuel; and (4) minimum-time with free fuel. The optimal control problems are then solved using an adaptive Legendre-Gauss-Radau collocation method.

**09:40 AM** **100: Reduced-Order Model for Spacecraft Swarm Orbit Design**

*Shane Lowe* and Simone D'Amico*

This paper introduces a reduced-order model for use in the design of spacecraft swarm missions which addresses swarm configuration, passive and active safety, swarm maintenance and reconfiguration, including the location and timeliness of maneuvers, and delta-v consumption, while meeting science requirements. Current methods and models proposed in the literature are limited by their computational complexity, which makes long- duration mission simulations impractical, and by a lack of explainability necessary for mission designers to understand the quantitative impacts of their design choices on mission parameters. The reduced-order model is validated through comparison with results obtained using high-fidelity numerical simulations.

# Session: Space Situational Awareness, Conjunction Analysis, and Collision Avoidance 1

### Room: Topaz 2, Time: 08:00 AM-10:00 AM

Session Chair: Piyush Mehta (West Virginia University)

**08:00 AM**

**104: Long-term encounters collision avoidance maneuver optimization with a multiple-impulse convex formulation**

*Zeno Pavanello*, Laura Pirovano and Roberto Armellin*

A method to compute fuel-optimal collision avoidance maneuvers for long-term encounters is presented.
The maneuver design is formulated as a convex optimization problem employing lossless convexification of the objective function, successive convexification of the dynamics, and projection and linearization of the keep-out zone constraint. It is then solved by state-of-the-art primal–dual interior-point algorithms. The proposed approach calculates optimal solutions for a large variety of initial conditions and different orbital scenarios. The execution time can be kept under 12 seconds for an optimization problem with thousands of variables and constraints, making it suitable for autonomous calculations.

**08:20 AM**

**110: Spaceborne Optimal Evasive Maneuvers Under Angle-Only Relative Navigation**

*Yazan Chihabi* and Steve Ulrich*

A novel guidance and control law that utilizes optimal control theory in combination with angle-only relative navigation observability criteria to obtain optimal evasive maneuvers in pursuer-evader formation flying of spacecraft is proposed in this paper. Specifically, the formulation determines a set of control maneuvers that render a pursuer's relative navigation system unobservable when attempting to estimate the range to the evader through the manipulation of the angle-only measurement profile. The newly-developed algorithm was tested for a far-range pursuer-evader scenario in low Earth orbit as well as on a highly elliptical orbit.

**08:40 AM**

**118: Uncertainty Propagation Of Perturbed Orbits Using High Order State Transition Tensors and Chebyshev Picard Method**

*Jennifer Good* and Ahmad Bani Younes*

Modeling and simulation for complex applications in science and engineering develop behavior predictions based on mechanical loads. Imprecise knowledge of the model parameters or external force laws alters the system response from the assumed nominal model data. Two issues complicate approaches for handling model uncertainty. First, most systems are fundamentally nonlinear. Second, series approximations are usually required, which demands that partial derivative models are available. Both issues have been significant barriers for previous researchers. Uncertainty propagation of perturbed orbital motion is proposed using high-order state transition tensors (STT) and Chebyshev-Picard Method.

**09:00 AM** **135: Investigation of Uncertainty Propagation Techniques for Spacecraft Conjunction Assessments**

*Amit Bala*, Kevin Schroeder and Jonathan Black*

In the spacecraft environment, uncertainty realism is critical in ensuring important space domain awareness tasks are completed effectively and accurately. Traditional long-term propagation results in the loss of Gaussian assumptions, fundamental to traditional conjunction assessment techniques among other crucial space domain awareness. The objective of this work is to develop a comparative study between different uncertainty representation techniques and provide insight for further developments in the field of uncertainty propagation while considering its implementation for conjunction assessments. The results of the study demonstrate the viability of sigma point generation via unscented transform as a viable candidate for uncertainty propagation, and establish preliminaries for further development in alternate state representations.

**09:20 AM** **141: How Space Weather affects Satellite Operations and Two Plans to improve the Process**

*Mark Vincent**

Uncertainties in predicted solar and geomagnetic indices affect routine satellite operations such as Drag Make-Up maneuvers and the calculation of the Probability of Collision with other objects. Contributions of future solar irradiance can be separated from present uncertainties in orbital elements. Use of proxies of Extreme Ultra-Violet (EUV) irradiance in atmospheric models has improved predictability of satellite drag, but new paradigms are necessary. One proposal includes ingesting real-time GOES satellite EUV irradiance data. A second proposal will utilize seismic imaging of the solar far side, enabling a predictive capability prior to sunspot active region rotation to the Earth-facing disk.

**09:40 AM** **156: The Effects Of Raising And Decay In Orbital Capacity Models**

*Davide Gusmini*, Andrea D'Ambrosio, Simone Servadio, Peng Mun Siew, Pierluigi Di Lizia and Richard Linares*

The sustainability of the Low Earth Orbit (LEO) environment is threatened by the growing number of Anthropogenic Space Objects planned to be launched in the next years. This paper investigates the evolution of objects residing in LEO through the MIT Orbital Capacity Assessment Tool (MOCAT), an evolutionary multi-shell multi-species source-sink model. The proposed novelty considers the flow of objects crossing multiple shells during orbit raising and deorbiting maneuvers, which increases the probability of collision and debris creation. To this aim, a higher fidelity MOCAT version including active satellites, derelicts, debris and rocket bodies has been developed and used.

## Session: Cislunar Space Missions and Operations 1

**Room: Onyx 2-3, Time: 10:20 AM-12:00 PM**

Session Chair: Diane Davis (NASA Johnson Space Center)

**10:20 AM**

**217: Optimal Spacecraft Constellation Analysis Utilizing Periodic Orbits for Maintaining Space Domain Awareness Within Cislunar Space**

*Connor Segal*, Kevin Schroeder and Jonathan Black*

Increasing numbers of spacecraft missions are soon expected to operate within the Cislunar orbital regime. Unfortunately, this region of space is beyond the tracking capabilities of some Earth-bound sensors. This problem therefore begets the need for on-orbit surveillance in order to maintain Space Domain Awareness (SDA). However, the highly dynamical nature of this environment greatly increases the complexity of providing consistent coverage. This paper proposes a methodology that leverages families of periodic orbits to analyze various constellation designs utilizing a genetic algorithm and systems engineering tool to determine combinations with optimal SDA. The resulting methodology demonstrates the potential for future investigations analyzing the SDA of Cislunar constellations.

**10:40 AM**

**227: Synodic Resonant Halo Orbits in the Hill Restricted Four-Body Problem**

*Rohith Reddy Sanaga* and Kathleen C. Howell*

Models in four-body problems (4BP) offer useful dynamical structures to investigate the impact of the Sun near the Earth-Moon libration points. Four-body models currently used include the Bicircular Restricted Four-Body Problem (BCR4BP) and the Quasi-Bicircular Four-Body Problem (QB4BP). This analysis is focused on the utility of the Hill Restricted Four-Body problem (HR4BP), a coherent model, in further investigation of the dynamics in Earth-Moon $L_2$ halo orbit region. Synodic Resonant orbits are constructed in the HR4BP and are transitioned to Higher Fidelity Ephemeris Model (HFEM) to evaluate the applicability of the HR4BP and provide insight into the dynamics in this region.

**11:00 AM**

**228: Periodic transfers that depart and return to an operating orbit using resonant orbit structures in the planar three-body problem**

*Noah Sadaka* and Kathleen C. Howell*

Many future satellite applications in cislunar space require periodic transfers that shift away from some operational orbit but return. Numerous resonant orbit families in the Earth-Moon Circular Restricted Three-Body Problem (CR3BP) possess a ratio of orbital period to lunar period that is sufficiently close to an integer ratio and can be exploited to uncover periodic transfers. By locating homoclinic connections associated with the operating orbit that incorporate resonant structures, and optionally linking them to resonant orbits, transfers are available for in-orbit refueling/maintenance as well as surveillance/communications applications that depart and return to the same phase in the operating orbit.

**11:20 AM** **287: Lunar Photon: Flight Dynamics Operations for the CAPSTONE Mission**

*Ryan Lebois*, John Carrico, Mike Loucks, Alisa Hawkins, Richard French, Federico Covitti and Federico Covitti*

CAPSTONE was launched on a Rocket Lab Electron launch vehicle from Launch Complex 1 (LC-1) in Mahia, New Zealand on June 28, 2022. After launch, the 12U CubeSat remained stowed in its deployer mounted on the top deck of the Lunar Photon spacecraft for approximately 6 days until its deployment on July 4, 2022. Over these 6 days, the Rocket Lab mission operations team planned and executed 7 maneuvers to progressively raise the apogee of both Lunar Photon and its payload until the final maneuver inserted both along a Ballistic Lunar Transfer (BLT) trajectory towards the Moon.

**11:40 AM** **290: Lunar Photon: SSC Doppler Processing with Variable Uplink Frequency**

*Ryan Lebois*, John Carrico, Mike Loucks, Alisa Hawkins, Richard French, Federico Covitti and Federico Covitti*

Spacecraft radios used for communications and radiometric tracking are generally designed for operations in a specific orbit regime (e.g., LEO, GEO, deep space) since operating conditions vary greatly between these regimes. The Lunar Photon spacecraft which carried CAPSTONE to its Ballistic Lunar Transfer (BLT) trajectory was unique, needing to operate from LEO to deep space. It was equipped with a Frontier-S by Rocket Lab radio to support coherent radiometric tracking at high ranges; however, this type of radio requires the received uplink frequency to be within a narrow range of the Best Lock Frequency (BLF), leading to challenges in lower orbits.

## Session: Rendezvous, Relative Motion, Proximity Missions, and Formation Flying 2

### Room: Topaz 3, Time: 10:20 AM-12:00 PM

Session Chair: Robert Melton (Pennsylvania State University)

**10:20 AM** **407: Rapid Synthetic Image Generation Using Neural Radiance Fields for Vision-based Formation Flying Spacecraft**

*Kai Matsuka*, Soon-Jo Chung and Christine Ohenzuwa*

In this paper, we develop a new method of rapidly simulating relative navigation cameras of formation flying spacecraft using the Neural Radiance Fields (NeRFs). First, the neural network learns the visual scene of a target spacecraft from a sparse set of images offline. Second, the trained network is queried to rapidly generate novel images of target spacecraft in previously unseen camera poses and lighting online. We evaluate the use of NeRF-rendered images for various vision-based navigation tasks such as object detection and keypoint matching.

**10:40 AM** **351: SQP Waypoint Generation for a Zero-Effort State Error Controller**

*Zachary Rhodes* and Brian Kaplinger*

This paper describesoptimal waypoints for state error feedback of a class of time-affine problems. A linear system of constraints on waypoints is found to govern the double-integrator and constant-gravity subproblems, and a similar continuity constraint is found to apply to the entire class of dynamical systems. The application problem demonstrates an autonomous waypoint generation algorithm for satellite orbital rendezvous, applying a SQP problem to identify a waypoint likely to minimize overall effort and then applying an algebraic closed-loop feedback control based on this selected waypoint for a piecewise trajectory.

**11:00 AM** **387: Challenge Problem: Close Proximity Operations for Spacecraft In-Space Servicing, Manufacture, and Assembly**

*Christopher "Chrispy" Petersen**

This paper introduces a challenge problem to the spacecraft community on In-space Servicing, Manufacture, and Assembly (ISAM). The problem is a subset of Spacecraft Rendezvous, Proximity Operations, and Docking (RPOD), and brings with it i.) a unique set equations of motion that include rotation, translation, and robotics, ii.) a variety of constraints and objectives that are specialized to RPOD, and iii.) a number of traditional and current control considerations. Two reference techniques, LQR & MPC, are applied as a reference to those who develop their own metods. Overall, this paper provides an entry point into spacecraft RPOD and is the first to provide a uniform reference to assess ISAM.

**11:20 AM** **209: Kinematic Batch Filter Formulation for Angular Velocity Estimation with Covariance Bounds**

*Siddarth Kaki* and Maruthi R. Akella*

The problem of estimating relative pose and angular velocity for uncooperative space objects has garnered great interest, especially within applications such as on-orbit assembly and satellite servicing. This paper presents new mathematical insights that permit a kinematic batch filter formulation for angular velocity estimation using quaternion measurements for relative orientation, thereby eliminating the need to know the moment-of-inertia of the target. In particular, a novel batch approach to computing the associated uncertainties for the angular velocity magnitude, spin-axis direction, and overall angular velocity vector estimates is presented and compared against previous recursive methodologies.

**11:40 AM** **210: Inertia-Free Pose and Angular Velocity Estimation Using Monocular Vision**

*Siddarth Kaki* and Maruthi R. Akella*

The problem of estimating relative pose and angular velocity for uncooperative space objects has garnered great interest, especially within applications such as on-orbit assembly and satellite servicing. This paper presents an upgraded open-source pose filtering software package that consists of convolutional neural networks for keypoint estimation, a nonlinear least-squares solver for static pose estimation, and a multiplicative extended Kalman filter for full pose filtering. In particular, new modules are introduced to perform moment-of-inertia-model-free angular velocity estimation, and also online moment-of-inertia estimation. Simulated time-series results are presented to evaluate the performance of the upgraded pipeline on flight-like hardware in real-time.

## Session: Satellite Constellations

### Room: Topaz 1, Time: 10:20 AM-12:00 PM

Session Chair: Hang Woon Lee (West Virginia University) and Smriti Nandan Paul (West Virginia University)

**10:20 AM**

**273: A Novel Formulation for the Multi-Stage Satellite Constellation Reconfiguration Problem: Initial Results**

*Hang Woon Lee* and Zeyu Liu*

We consider the problem of optimizing the reconfiguration of a constellation of maneuverable satellites through multiple stages in order to maximize the total observation rewards collected by covering a set of spot targets. To address this problem, we propose a new mathematical formulation and a solution method that leverages this formulation. Our algorithm reduced computation time through the ordering and filtering of sub-optimal constellations. Through computational experiments, we compare the performance of our approach with that of a previously proposed method. The initial results suggest that the proposed method outperforms the previous method in terms of the total observation rewards collected and the algorithm runtime required for small-scale problems.

**10:40 AM**

**308: Dynamical characterization of endogenous conjunctions within the Starlink constellation**

*Sui Chen and Davide Amato**

Short-term, high temporal resolution conjunction assessments were conducted within the Starlink constellation. A hypothetical scenario was considered where one satellite failed and its orbital evolution followed natural dynamics subject to perturbations present in space, while all other operational satellites followed their nominal orbits. Simulation results show that 92.3% of the out-of-plane conjunctions occurred at high latitudes beyond $\pm 50^\circ$ with relative speed lower than 5.3 km/s and only a small portion of the out-of-plane conjunctions were high-speed and occurred closer to the equator. The findings are expected to aid the future planning of endogenous collision avoidance strategies by the constellation operators.

**11:00 AM**

**333: SunRISE is Coming: Mission Design and Navigation for the First Space-based Radio Interferometer**

*Jeffrey Stuart*, Juan Senent, Kenza Boudad, Reza Karimi and Dianna Velez*

The Sun Radio Interferometer Space Experiment (SunRISE) mission will place six space vehicles fitting the 6U CubeSat form-factor into a GEO graveyard orbit, where they will fly in a passive cluster to establish the first space-based interferometer. This low-cost mission presents a number of unique challenges in regards to mission design and navigation, in particular the tight coupling between orbital motion and the scientific performance of the observatory. This work provides an update on the current status of SunRISE as the mission completes integration and test and prepares for flight readiness.

**11:20 AM** **338: Hybrid Constellation Design of CubeSats for Monitoring Hurricanes**

*Pardha Sai Chadalavada* and Atri Dutta*

In this paper, we propose a novel mission design concept referred to as a hybrid constellation in which multiple formation-flying CubeSat clusters are deployed in a traditional multi-plane constellation configuration. Considering an application to hurricane monitoring over the Atlantic warm pool and mainland United States, we develop a methodology to determine the optimal configurations for the specific case of two CubeSats in a leader-follower formation within each cluster. Numerical simulations depict the effect of the formation design choices on the hybrid constellation design solutions.

## Session: Space Situational Awareness, Conjunction Analysis, and Collision Avoidance 1

### Room: Topaz 2, Time: 10:20 AM-12:00 PM

Session Chair: Piyush Mehta (West Virginia University)

**10:20 AM** **169: OPERATIONAL VALIDATION OF A SPACECRAFT PATTERN-OF-LIFE CHARACTERIZATION ALGORITHM**

*Casey Heidrich, Mark Moretto, Karina Rivera* and Marcus Holzinger*

Behavior classification and inference for unowned space objects represents a challenging task in space situational awareness. This work applies a spacecraft pattern-of-life detection algorithm to electro-optical measurements obtained from a 0.6 meter Raven-class telescope located in Boulder, CO. An observation campaign is undertaken to collect data on space objects of interest in the geostationary belt. The algorithm is applied to experimentally obtained data in order validate its performance on operational satellites. Results are shown to accurately characterize space objects in the geostationary belt and enable behavior classification using electro-optical sensors.

**10:40 AM** **179: RESIDENT SPACE OBJECT IDENTIFICATION IN ARBITRARY UNRESOLVED SPACE IMAGES**

*Joseph Anderson*, David Zuehlke, Annika Anderson, Alan Lovell and David Canales Garcia*

Identifying resident space objects (RSOs) in arbitrary space imagery with little a-priori information is a challenging, yet crucial next step in space-domain awareness applications. This work proposes improvements to an existing RSO identification process for unresolved space images. The algorithm has three main phases: image processing, star elimination, and RSO association. Star elimination and RSO association use nearest neighbor association and thresholds on inertial frame-to-frame motion of observations to associate objects. Given a set of unresolved space images contiguous in time, the product of the algorithm presented is a set of measurements for orbit estimation.

**11:00 AM** **198: Low-thrust Collision Avoidance Design for Leo Missions With Return to Nominal Orbit**

*Andrea De Vittori*, Gabriele Dani, Pierluigi Di Lizia and Roberto Armellin*

This work investigates the design of optimal and computationally efficient low-thrust Collision Avoidance Maneuvers (CAMs) in the LEO regime. A potential collision is prevented thanks to two different CAM policies. The first one enforces a certain threshold on the Probability of Collision (PoC) at the Time of Closest Approach (TCA); then, the spacecraft targets a point belonging to its nominal orbit. For this purpose, the conjunction dynamics of the two objects are presented in a Cartesian reference system and then projected onto the B-plane, centred on the secondary object. The second method forces the satellite to match the original Keplerian parameters, leaving out the true anomaly.

**11:20 AM** **223: SPACE OCCUPANCY CONJUNCTION FILTER**

*Ana S. Rivero, Claudio Bombardelli and Rafael Vazquez**

Assessing the risk of in-orbit collisions is becoming an increasingly challenging task. In particular, detecting all possible close approaches in a large catalog is computationally demanding and conjunction filters are typically used to reduce the burden. We present a new conjunction filter using the recently-introduced concept of space occupancy, based on a zonal-harmonic perturbed two-body-problem model. Being formulated in close analytical form, it maintains the computational simplicity of the classical apogee-perigee filter while improving its efficiency. The effectiveness of the filter against the classical apogee-perigee filter is evaluated in low-Earth orbit scenarios using a high-fidelity perturbation model.

**11:40 AM** **224: Extending the Utility of Multi-Fidelity Space Object Uncertainty Quantification with Vinti Theory**

*Trevor Wolf* and Brandon Jones*

Within the Space Domain Awareness (SDA) community, there is a need for methods that can rapidly and accurately propagate space objects' uncertainty. Multi-fidelity methods are one solution to this problem and have demonstrated success for applications in Low Earth Orbit (LEO). In this work, we extend the utility of multi-fidelity uncertainty quantification to regimes beyond LEO through Vinti theory. Using a Vinti propagator as a low-fidelity model in a stochastic collocation method, we can accurately approximate a particle uncertainty representation without the computational cost of solely using an expensive high-fidelity numerical propagator.

**12:00 PM** **226: Short-Term Collision Probability Caused by Debris Clouds**

*Cristina Parigini, Reem Algethaime and Roberto Armellin**

We propose a method for fast estimating the collision probability in a short window following the cloud generation. A Lambert targeting problem is employed to determine all the locations where the collision probability is non-negligible. Then, the Lambert problem and state transition matrix are used to obtain the image of the target body in the spread velocity space, where the collision probability computation is performed. High order Taylor expansions and automatic domain splitting technique are applied to perform and control the accuracy of the integration of the collision rate, needed to obtain the collision probability.

## Session: Attitude Dynamics, Determination and Control 1

### Room: Topaz 1, Time: 01:30 PM-03:10 PM

Session Chair: Dr. Peter Lai (USSF SSC / LinQuest Corporation)

**01:30 PM**

**121: Attitude-Orbit Integrated Control of Solar Sail with Single-Axis Gimbal Mechanism**

*Toshihiro Chujo*, Kei Watanabe and Yuki Takao*

A new attitude control for solar sails is proposed using a single-axis gimbal mechanism and three-axis reaction wheels. To counteract the disturbance torque due to solar radiation pressure (SRP), we apply the gimbal to varying the geometrical relationship between the center of SRP and center of mass of the spacecraft such that the disturbance torque is zero. Even if the angular momentum is accumulated in the reaction wheels due to some errors, it can also be unloaded by using the gimbal, for which we propose a time-optimal control. The validity of the method is verified in the attitude-orbit integrated simulations.

**01:50 PM**

**144: Online Estimation of Unknonwn Parameters of Highly Flexible Spacecraft using Integral Concurrent Learning and Kane's Equation**

*Nicolo Woodward*, Andrew J. Sinclair and Riccardo Bevilacqua*

This paper proposes a method to develop a high-fidelity model of a spacecraft with a flexible appendage using Kane's equation and design an adaptive controller that learns unknown parameters of the flexible appendage after some finite excitation, tracking a desired trajectory. The controller uses integral concurrent learning, an adaptive scheme that records inputs and outputs to estimate unknown parameters of the system. After tuning the control gain matrices at different initial conditions, the controller achieves the objective to track a desired trajectory while accurately learning the unknown physical parameters of the flexible appendage by only using the recorded measurements.

**02:10 PM**

**151: Applications of Reflective Control Devices for Position and Attitude Control in the Sun-Earth Lagrange Points**

*Alejandro Cabrales Hernandez**

A novel method of obtaining orbit and attitude control of satellites using only Reflective Control Devices (RCDs) around Sun-Earth Lagrange point 2 (SEL2) is presented. The control algorithm is derived in which the limited control authority from the fixed-orientation RCDs is re-prioritized depending on the mission objective such as station keeping or active high-accuracy attitude tracking. The use of RCDs could enable the extension of mission lifespan to future missions operating at SEL2 due to the reduction or elimination of propellant usage.

**02:30 PM** **163: Spacecraft Dynamics Analysis Using Point-Mass Model of Human Motion**

*Galen Bascom*, Leah Kiner and Hanspeter Schaub*

As concepts for spacecraft with larger populations of humans aboard emerge, the need for an implementable model of the effects of human and cargo motion grows. A point-mass model for that motion is created, and the effects on spacecraft rotational and translational motion derived. Using a back-substitution method developed in previous work on multi-body dynamics, an efficient and modular software implementation of the dynamics is presented. The moving point-mass along a spinning spacecraft hub is simulated, demonstrating complex attendant behaviors. The sensitivity of the effects on the hub to both the mass and speed of the moving object are investigated.

**02:50 PM** **180: Zero Placement for Discrete Time Systems**

*Jer-Nan Juang* and Richard Longman*

Spacecraft sensors often have stringent pointing accuracy requirements. The bandwidth using classical feedback design is often limited. Inverse models are considered here for good performance beyond the bandwidth. Previously this has not been an option, digital systems usually have unstable inverse. Here, additional zero-order holds are introduced allowing one to do zero placement. A matrix algorithm is developed, making discrete models have a stable inverses. Issues of where to place zeros and how to make good performance between samples are studied. Results can be used to modify many control approaches to aim for zero error instead of being band limited.

## Session: CubeSat and SmallSat Missions

### Room: Onyx 2-3, Time: 01:30 PM-03:10 PM

Session Chair: Arnaud Boutonnet (European Space Agency / ESOC)

**01:30 PM** **145: Relative Phasing And Observations Overlap: Low-Thrust Trajectory Design Options for the INCUS Mission**

*Kenza Boudad* and Quinn Kostelecky*

A recently selected NASA Earth Venture Mission, the INvestigation of Convective UpdraftS (INCUS) aims to further the understanding of the formation of tropical convective storms. This paper outlines two aspects of the low-thrust, three-smallsats constellation design. First, the in-track offsets between vehicles are determined such that the ground observations are separated by a specified time interval. Second, an algorithm is developed to design the transfers sequence to deliver the spacecraft to their nominal configuration along the science orbit. Analytical solutions for both aspects are derived and verified, allowing rapid design of the constellation's initialization sequence.

**01:50 PM** **200: Origami Application to Space Mirror Reflectors**

*David Garcia* and Robert Bettinger*

A number of origami patterns are presented in order to augment lighting conditions in rendezvous and proximity operations by incorporating deployable solar reflectors. Weight, size, and cost are all restrictions that must be accounted for when designing a spacecraft. The focus is to apply proven modern origami designs to maximize a space mirror's surface area but storing it in a compact form. This research was done to fit light weight solar reflector payloads within a cube satellite or small satellite and to understand the potential of different pattern applications through the study of Palmer and Shafer's origami design.

**02:10 PM** **342: Multi-CubeSat Formation Design for a High-Precision Timing and Ranging Experiment in LEO**

*Raj Patel*, Penina Axelrad and Christopher Flood*

The concept of creating a large, distributed sensor by precisely operating a formation of small satellites has been demonstrated in several successful formation flying missions. This paper presents short baseline, CubeSat-scale, LEO formation designs that provide the translational and angular geometry required to achieve precision ranging, timing, and target pointing with small separations. Multi-target attitude control using body pointing and gimbals is required, to maintain a chain of links between all satellites in the formation and point at a common ground, orbiting, or distant space target. The astrodynamics simulation and visualization framework, Basilisk, is used for high-fidelity and realistic formation analysis.

**02:30 PM** **365: 3UCubed: The IMAP Student Collaboration CubeSat Project**

*Sanjeev Mehta*, Noé Lugaz, Lindsay Bartolone, Laura Peticolas, Marcus Alfred, Marc Lessard, Lynn Cominsky, Sonya Smith and May-Win Thein*

The 3UCubed project is a 3U CubeSat being jointly developed by the University of New Hampshire, Sonoma State University, and Howard University as a part of the NASA Interstellar Mapping and Acceleration Probe (IMAP) student collaboration. This project consists of a multidisciplinary team of undergraduate students from all three universities. The science goal of 3UCubed is to better understand how Earth's polar thermosphere responds to particle precipitation, solar wind forcing, and internal magnetospheric processes.

**02:50 PM** **406: Slew Maneuver Simulation and Stabilization Settling Time Analysis for the VISORS Space Telescope Mission**

*Micah Schuman and Hyeongjun Park**

Distributed spacecraft systems have revolutionized a new class of missions for navigation, communications, remote sensing, and scientific research for civilian and military purpose. A distributed virtual telescope mission, VISORS (Virtual Super-resolution Optics with Reconfigurable Swarms), is being developed for higher resolution imaging of the solar corona to determine the existence of hypothesized heat-release bands. In this paper, the attitude determination and control systems for two CubeSats of the VISORS mission are introduced, and the slew maneuvers to form a distributed space telescope are simulated. Finally, the settling time for attitude stabilization is analyzed based on the mission requirements to obtain images.

## Session: Spacecraft Guidance, Navigation and Control 2

**Room: Topaz 3, Time: 01:30 PM-03:10 PM**

Session Chair: James Thorne (Institute for Defense Analyses (IDA))

**01:30 PM**

**249: Asymptotically Stable Simple Adaptive Control For Free-Floating Space Manipulators**

*Parker Stewart* and Steve Ulrich*

This paper solves the problem of trajectory control of n-link free-floating space manipulators under perturbations and uncertainties. The developed strategy consists of a joint-based control scheme for tracking the Cartesian coordinates of the end-effector of an n-link free-floating space manipulator while ensuring asymptotic stability of the tracking errors and adaptive gains. Numerical simulations compare the performance of the adaptive controller against a nonadaptive controller in the context of a 10x10 cm square trajectory. Finally, experimental validation is performed at Carleton University's Spacecraft Robotics and Control Laboratory to demonstrate that the adaptive control strategy outperforms its nonadaptive counterpart, especially under off-nominal conditions.

**01:50 PM**

**266: Backstepping-based Tracking Controller Using Orbit-Attitude Interactions of Spacecraft**

*Jinah Lee* and Chandeok Park*

This study proposes a backstepping-based tracking controller which uses orbit-attitude interactions originating from the reaction wheel assembly (RWA). The orbit-attitude interaction arising from the RWA arises when the dynamics of reaction wheels are incorporated into the integrated orbit-attitude dynamic systems. The proposed controller does not get rid of all the nonlinear dynamical terms, but rather it may benefit from those terms. Numerical simulations justifies the proof of the proposed tracking system, compare with other control systems, and reveal its characteristics. The backstepping approach would efficiently use the nonlinear interactions to result in better performances in terms of control accuracy and timely response.

**02:10 PM**

**292: On Constrained Feedback Control of Spacecraft Orbital Transfer Maneuvers**

*Simone Semeraro*, Ilya Kolmanovsky and Emanuele Garone*

The paper revisits a Lyapunov-based feedback control to implement spacecraft orbital transfer maneuvers. The spacecraft equations of motion in the form of Gauss Variational Equations (GVEs) are used. By shaping the Lyapunov function using barrier functions, we demonstrate that state and control constraints during orbital maneuvers can be enforced. Simulation results from orbital maneuvering scenarios are reported. The synergistic use of the reference governor in conjunction with the barrier functions is proposed to ensure convergence to the target orbit (liveness) while satisfying the imposed constraints.

**02:30 PM**

**328: Mass Property Estimation for Rigid Body Spacecraft on the Special Euclidean Group SE(3) and its Tangent Bundle TSE(3)**

*Brennan McCann*, Marco Fagetti, Morad Nazari, Matthew Wittal and Jeffrey Smith*

In this paper, a rigid body state estimation scheme is developed on the Lie group describing rigid body motion, i.e. the special Euclidean group (SE(3)), and its tangent bundle (TSE(3)). In addition to the states of the system, the filter estimates unknown mass properties of the rigid body. An unscented Kalman filter on SE(3) and TSE(3) is employed to address uncertainties in the states and mass properties. This methodology accounts for uncertainties while considering rotational-translational coupling and avoids singularities or non-uniqueness issues. The algorithms are validated on a generic model of a Gateway logistics vehicle.

**02:50 PM**

**107: PlasmaPump: A novel hybrid rocket engine design using thermionic emission, quantum tunneling and plasma to boost efficiency**

*Archit Kalra**

Increasing the efficiency of modern rockets has been an elusive quest in past decades due to thermodynamic limits on rocket performance. This paper describes the development of a rocket turbopump schematic called PlasmaPump, which facilitates conventional combustion reactions for takeoff, but uses the processes of thermionic emission, quantum tunneling and plasma production to switch to plasma propulsion once the rocket is in space. I calculate the efficiency of the plasma propulsion component of the model to be 0.734 and discuss the implications. Next steps include constructing physical models of the hybrid engine to test efficiency in real-world systems.

## Session: Trajectory/Mission/Maneuver Design and Optimization 3

**Room: Topaz 2, Time: 01:30 PM-03:10 PM**

Session Chair: Stefano Campagnola (Jet Propulsion Laboratory)

**01:30 PM**

**366: Path Control Constraint Handling for Differential Dynamic Programming**

*Bryn Fanger* and Ryan Russell*

A comprehensive analysis of four path control constraint methods for thrust magnitude limitations applied to a Hybrid Differential Dynamic Programming (HDDP) algorithm is presented. The methods evaluated are the Heaviside Augmented Lagrangian, inequality Augmented Lagrangian, box, and implicit. Cartesian and spherical control parameterizations with scaling schemes are also examined for some methods. These techniques are tested on a variety of trajectory optimization problems with up to 11 revolutions to reveal strengths of each method and to determine best applications for each.

**01:50 PM**

**203: Constellation Design to Support Cislunar Surveillance Leveraging Sidereal Resonant Orbits**

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

There is a growing interest in trajectories to support missions throughout cislunar space, specifically the region beyond GEO to the vicinity of the Moon and the $L_1$ and $L_2$ libration points. Multiple satellites, together, assist with the monitoring and surveillance of cislunar space for long-term sustainable operations. This investigation explores resonant orbits and libration point orbits in sidereal resonance for hosting observer satellites that span cislunar space. Constellations of observers are designed, and options for various different observer orbits are explored. The efficacy of the constellations for surveillance applications is evaluated in both the CR3BP and ephemeris models.

**02:10 PM**

**260: Optimal Control for Formation Reconfiguration Problems Using Pseudospectral Methods**

*Alessia De Iuliis*, Davide Costigliola and Lorenzo Casalino*

Two mathematical methods to solve optimal control problem for minimum-fuel low-thrust formation reconfiguration are presented and compared. The problem is discretized with the Legendre Pseudospectral method: direct and indirect formulations are developed and applied to specific cases. The Bellman's principle of optimality is incorporated as part of an antialiasing technique to map the discrete solution to the continuous-time domain. In the indirect formulation a smoothing technique is applied to enhance convergence properties. Results show that the indirect method can solve optimization problems to good accuracy with poor initial guesses and few nodes, overcoming the inability of the direct Pseudospectral.

**02:30 PM**

**359: Blue Ghost Lunar Lander Orbital Maneuver Statistical Analysis**

*Daniel Guerrant*, Alisa Hawkins, J.P. Carrico III and Scott Yantek*

Blue Ghost is a lunar lander made by Firefly Aerospace per a NASA Commercial Lunar Payload Services contract and landing in Mare Crisium in 2024. ASI by Rocket Lab is providing the flight software, ground software, and guidance, navigation, and control (GNC) services. This paper covers its orbital maneuver GNC implementation and expected performance by Monte Carlo simulations of both the flight software and maneuver execution workflow. The trajectory from launch vehicle separation, three Earth orbits, 16 days in lunar orbit, and up to but not including powered descent should take under 950 m/s of $\Delta V$, including statistical and launch window budgets with margin.

**02:50 PM**

**312: Trajectory Reverse Engineering: A General Strategy for Transferring Trajectories Between Flight Mechanics Tools**

*Ricardo Restrepo**

Space exploration missions are usually a product of the collaboration between different teams, generally involving the use of different flight mechanics tools. Each tool has its own set of dynamical and numerical models. Slight differences between the models can cause unacceptable differences between the shared trajectories. To overcome this issue, we propose a trajectory-sharing process via SPK kernels, which are agnostic to the models used. A judicious kernel scan is used to recover the original trajectory. Examples of transfer solutions between the NASA tools Monte and Copernicus are presented, including Earth-to-Moon transfers, interplanetary trajectories, Moon tours, and icy-worlds orbiter solutions.

## Session: DART Navigation

### Room: Onyx 2-3, Time: 03:30 PM-04:30 PM

Session Chair: Sonia Hernandez (Continuum Space Systems)

**03:30 PM** **360: Double Asteroid Redirection Test (DART) Final Mission Design and Flight Path Control**

*Justin Atchison*, Frank Laipert and Maria McQuaide*

This paper reports the final mission design and flight path control for the DART mission. DART launched on 24 Nov 2021 and executed 7 TCMs prior to impacting Dimorphos on 26 Sep 2022. The final encounter conditions balanced constraints on impact geometry and the objective to maximize the imparted period change in Dimorphos's orbit. The TCMs maintained these impact conditions and mitigated launch dispersions, model uncertainties, and residual delta-v associated with the thruster-only attitude control. The final TCM, 24 hours prior to impact, placed DART on an impact trajectory toward the system with less than 200 meters of error.

**03:50 PM** **234: Optical Navigation for the DART Mission**

*Brian Rush, Declan Mages*, Andrew Vaughan, Julie Bellerose and Shyam Bhaskaran*

The DART mission launched in November 2021 to impact the asteroid Dimorphos in September 2022. The goal of this technology demonstration mission was to test orbital deflection as a method of defense against potential asteroid or comet hazards. The precise targeting needed to hit such a small body requires the use of optical navigation imaging during the final month of the approach. We describe the contribution Opnav made to the navigation of the DART spacecraft and the particular challenges faced when planning and analyzing the Opnav images.

**04:10 PM** **238: Double Asteroid Redirection Test (DART) Mission: Processing, Analysis, and Modeling of the Reaction Control System Thruster Delta-V For Orbit Determination**

*Dianna Velez*, Julie Bellerose, Ian Murphy, Tim McElrath and Danielle Holzberger*

The Double Asteroid Redirection Test (DART) spacecraft impacted the asteroid Dimorphos on September 26, 2022. Throughout the mission, a variety of activities utilized different attitude control modes with unique restrictions. For 3-axis attitude control the spacecraft was exclusively equipped with 12, but operated with only 8, hydrazine thrusters. The attitude thrusting was nominally balanced over time but unbalanced at times. This work describes the new tools and features to access, process, and model relevant telemetry for navigation analysis, the methods used to handle attitude control deadbanding effects during final approach, and the guidance & control and navigation teams’ lessons learned.

## Session: Attitude Dynamics, Determination and Control 1

### Room: Topaz 1, Time: 03:30 PM-04:50 PM

Session Chair: Dr. Peter Lai (USSF SSC / LinQuest Corporation)

**03:30 PM** **185: Design of a reaction wheel system for CubeSat CHASQUI II Attitude Control**

*Jesus Antonio Tapia Gallardo, Mauricio Alejandro Aldave Amado, Gerardo Emilio Cevallos Robles* and Paul Palacios*

CHASQUI-II is a 1U educational CubeSat developed by the Universidad Nacional de Ingeniería-Peru. This paper describes the design process of the reaction wheel that will be used in the ADCS of the nanosatellite. First, based on previous designs, the optimal parameters for the wheel were selected, according to the system requirements. In addition, a Von Misses stress analysis was performed in Inventor to ensure the reliability of the model. Then, three motors were characterized in order to compare their performance and choose the most suitable one. Finally, the motor-wheel system was simulated together with the rest of the satellite on one axis in MATLAB and Simulink, implementing a servo system

**03:50 PM** **191: Dual Quaternion Relative Dynamics for Gravity Recovery Missions**

*Ryan Kinzie*, Riccardo Bevilacqua and Dongeun Seo*

A dual quaternion modeling approach is compared to traditional modeling methods for modeling the 12 degree-of-freedom coupled relative dynamics of a spacecraft its test mass. The novelty of this research is that although the dual quaternion modeling approach has shown significant promise in past research for efficiently and accurately modeling the coupled relative dynamics of spacecraft, this approach has never been employed for gravity recovery missions. It is hoped that this research will be able to prove that the dual quaternion modeling approach has the potential to increase the accuracy of gravity recovery missions.

**04:10 PM** **222: Orbit and Attitude Coupling in the Full Higher-Fidelity Ephemeris Model within the context of the Geometric Mechanics Framework**

*Annika Anderson*, Brennan McCann, David Canales Garcia and Morad Nazari*

It is crucial to be able to predict the attitude of  spacecraft to guarantee mission success within the Cislunar realm. To that end, the orbit/attitude coupling for the full N-body problem is presented first. Then, trajectories computed in the circular restricted full three-body problem (CRF3BP), previously proposed by the authors, are utilized as initial guesses for a full ephemeris model, where the gravitational field of perturbing bodies and the eccentricity of the Moon affect the motion of the rigid-body spacecraft. An analysis on orbit/attitude coupling is sought for planar Lyapunov orbits obtained in the CRF3BP.

## Session: Spacecraft Guidance, Navigation and Control 2

**Room: Topaz 3, Time: 03:30 PM-04:50 PM**

Session Chair: James Thorne (Institute for Defense Analyses (IDA))

**03:30 PM** **303: Preliminary Design of the Dragonfly Navigation Filter**

*Ben Schilling*, Timothy McGee, Ryan Mitch and Ryan Watson*

Dragonfly is scheduled to begin exploring Titan by 2034 using a series of multi-kilometer surface flights. This paper outlines the preliminary design of the navigation filter for the Dragonfly Mobility subsystem. The software architecture and filter formulation for redundant IMUs, lidar, and visual odometry are described in detail. Special discussion is given to developments to achieve multi-kilometer surface flights, including optimizing sequential image baselines, modeling correlating image processing errors, and an efficient approximation to the Simultaneous Localization and Mapping (SLAM) problem.

**03:50 PM** **309: Angles-Only Tracking and Navigation for Approach and Rendezvous in Geosynchronous Orbits**

*Justin Kruger*, Simone D'Amico, Christopher Roscoe and Jason Westphal*

Onboard relative navigation for geosynchronous rendezvous using vision-based sensors poses unique challenges for target tracking and orbit determination algorithms. Uncertainties in a priori state information require intelligent methods for discriminating potentially non-cooperative targets amongst multiple dynamically-similar objects. Tracking is needed during fast rendezvous approaches and continuous thrusting arcs, presenting challenging angles-only observability. This paper describes usage of new on-board tracking models, short-arc orbit determination methods, and system state augmentations to extend an angles-only navigation architecture to the geosynchronous environment. High-fidelity simulations of single-observer rendezvous and multi-observer target tracking demonstrate robust performance in support of autonomous satellite inspection and servicing.

**04:10 PM** **321: Recursive Update Filtering: A New Approach**

*Kristen Michaelson*, Andrey Popov and Renato Zanetti*

Maintaining an accurate statistical representation of the states and uncertainty in a nonlinear dynamical system is a difficult task. The Extended Kalman Filter (EKF) assumes a Gaussian distribution and provides a state estimate and associated covariance. Recursive extensions to the EKF, such as the Iterated EKF and the Recursive Update Filter (RUF), improve the accuracy of the EKF with little additional computational cost. In this article, we present the Bayesian Recursive Update Filter (BRUF), a variant of the RUF based on Bayesian principles. We show that even with relatively few recursions, the proposed update impoves significantly on the EKF update.

**04:30 PM** **399: Psuedospectral Optimal Control of Spacecraft Rendezvous with Combined Differential Drag and Lorentz Forces**

*Mohamed Shouman and Ahmed Atallah**

Trajectory tracking control with minimum fuel consumption is a key technology in spacecraft rendezvous missions. This creates a need to exploit the space environment forces in various orbit control applications. In this paper, optimal control action is derived from solving a nonlinear optimal control problem for a satellite constellation to minimize the required maneuver time with combined differential aerodynamic drag and Lorentz forces. It proposes an optimal trajectory for rendezvous missions by transcribing Gauss Pseudospectral method, whereas the solution of the nonlinear programming is obtained by implementing the sequential quadrature programming algorithm to use the Legendre polynomial roots as nodes.

## Session: Trajectory/Mission/Maneuver Design and Optimization 3

### Room: Topaz 2, Time: 03:30 PM-04:50 PM

Session Chair: Stefano Campagnola (Jet Propulsion Laboratory)

**03:30 PM** **166: Ballistic Lunar Transfer Design Using the Deep Space Trajectory Explorer**

*Jeremy Petersen, Brian McCarthy* and Diane Davis*

In 2020, NASA released the agency's lunar exploration program overview. An understanding of the cislunar gravitational environment is crucial to the success of these program. Given the chaotic nature of a multi-body system, preliminary path planning is challenging. Development of tools to streamline the trajectory design process that leverages dynamical structures in cislunar space is critical. The Deep Space Trajectory Explorer (DSTE) was developed as a JavaFX-based tool to facilitate trajectory design in multi-body systems using interactive visualization techniques. In this investigation, the functionality of DSTE is extended to construct ballistic lunar transfers (BLTs) to libration point orbits in cislunar space.

**03:50 PM** **246: Adaptive Roadmap Generation for Trajectory Design in the Earth-Moon System**

*Kristen Bruchko* and Natasha Bosanac*

In this paper, a probabilistic roadmap is generated to summarize the solution space near the Moon in the Earth-Moon circular restricted three-body problem. This roadmap is a directed, weighted graph formed by adaptively selecting nodes that reflect possible states and edges that capture their connectivity. Then, the roadmap is rapidly searched using graph search algorithms to construct a variety of distinct initial guesses for transfers between periodic orbits. The goal of this approach is to reduce the reliance on a human-in-the-loop by constructing a single roadmap that can be rapidly searched to construct complex initial guesses for various trajectories.

**04:10 PM** **326: Leveraging the Moon and Stable Libration Point Orbits Around L4/L5 to Observe the Solar Corona**

*Sebastian Doroba*, Rasika Kale, David Canales Garcia, Hancheol Cho, Stephen Eikenberry, Octavi Fors, Jose Maria Gomez and Andrea Richichi*

There is a significant interest in studying the Solar corona as it can provide copious amounts of information about the Sun. The objective of the proposed investigation is to provide an efficient approach to observe the Solar corona by using the Moon as an occulter to suppress the blinding luminosity of the Sun's surface. By exploiting the stable Libration points (L4 and L5) within the Cislunar region, a spacecraft will be within proper position to observe the Solar corona with an orbit requiring minimal station keeping.

**04:30 PM** **124: Using NRHO Invariant Funnels to Target Enceladus South Pole**

*Jared Blanchard*, Martin Wen-Yu Lo, Brian Anderson, Ricardo Restrepo and Damon Landau*

The south pole of Enceladus is a particularly interesting location in the search for life due to the jets spouting from large cracks in the crust, known as "tiger stripes." Near rectilinear halo orbits (NRHOs) are an attractive mission design solution to position a spacecraft near the south pole for observation of these jets. This work illustrates how to use invariant funnels to target NRHO periapses from resonant orbits and describes a catalog that can be used by mission designers to determine total $\Delta v$ budgets from various resonances. It also explores the connection between Jacobi constant and the availability of resonances for flyby orbits.

# Wednesday, January 18

## Session: Atmospheric Re-entry Guidance and Control

### Room: Onyx 2-3, Time: 08:00 AM-10:00 AM

Session Chair: Davide Guzzetti (Auburn University)

**08:00 AM** **152: Terminal Landing Guidance Law using Analytic Gravity Turn Trajectory**

*Seungyeop Han* and Koki Ho*

This paper introduces the terminal landing guidance law based on the analytic solution of gravity-turn trajectory. Characteristics of the derived solution are investigated, and the solution is used for the generation of a reference two-dimensional vector field that satisfies terminal landing conditions. In addition, the vector field is further expanded to consider ground collision avoidance as well as three-dimensional problem. A nonlinear control law is applied to track the reference vector efficiently within a finite time. The effectiveness of the proposed method is demonstrated through nonlinear numerical simulations and performances are compared with existing methods.

**08:20 AM** **177: Constrained Hypersonic Trajectory Optimization Using Gaussian Quadrature Collocation**

*Katrina Winkler* and Anil Rao*

The constrained trajectory optimization of a hypersonic vehicle is considered. The optimal control problem is solved in two different scenarios. In the first scenario, the objective is to minimize the terminal velocity. In the second scenario, the objective is to minimize the total heat load during entry. The solutions are obtained using adaptive Gaussian quadrature collocation and are compared to those obtained in previous research where a Sequential Convex Programming (SCP) method was employed.

**08:40 AM** **181: Optimal Range Capabilities for Low-Lift-to-Drag Ratio Entry Vehicles**

*Daniel Engel* and Zachary Putnam*

Optimal control problems for maximizing the range of a low-lift-to-drag ratio entry vehicle at Mars are solved. These optimal control problems consider both vehicles using bank-angle steering as well as direct force control to steer during entry. The maximum longitude and maximum latitude problems are considered. The latter allows for an optimal range capability to be created and compared between constant bank or angle of attack and sideslip angle commands. The resulting optimal control inputs often differ significantly between bank-angle steering and direct force control vehicles, the latter of which can extend range by lowering drag through sideslip angle reversals during entry.

**09:00 AM** **388: A Passive Guidance System for the Sample Return Mission from the International Space Station**

*Youngro Lee* and Dae Young Lee*

The ability to return a small payload from International Space Station to a target on the ground will be in high demand in the future. This paper presents a trajectory analysis for the onboard guidance system development of the mission, especially focused on the reentry phase. Trajectory simulations reveal that a specific landing location confines a desired return trajectory, so the optimal reentry interface (RI) and ballistic coefficient (BC) of the reentry vehicle for precision landing exist. Furthermore, concurrent optimization of RI and BC can counteract atmospheric uncertainties and orbit control errors. A BC adjustable reentry vehicle design is proposed.

**09:20 AM** **400: Control strategy for Aerocapture using concepts of Model Predictive Control**

*Shruthi Nagabhushana*, Robert Bitmead and Ahmad Bani Younes*

This paper presents a control strategy to the aerocapture problem in a closed-loop sense by including in-flight sensor data into the optimal control calculation to profit from the reduced sensitivity offered by feedback control. The approach is to solve a small number of in-flight optimal control problems using concepts from Model Predictive Control (MPC) in a hybrid setting, i.e. continuous vehicle dynamics, quasi-continuous control signal (bank angle) and discrete resolutions. In the paper, the problems will be defined, and performance is examined using simulations of flight dynamics and commercial optimal control software. Properties of MPC such as recursive feasibility are discussed, and state estimation error quantification is brought into picture.

09:40 AM **420: A Monte Carlo Analysis of Contingency Optimal Guidance for Mars Entry**

*Emily Palmer* and Anil Rao*

A Monte Carlo Analysis is completed to analyze a novel contingency optimal guidance strategy. The strategy is applied to a Mars Entry problem in which it is assumed there is a random error in the surface level atmospheric density model. The contingency plan utilizes the reference optimal control problem formulation, but modifies the objective functional to maximize the margin between limit and the current constraint value. In order to analyze the effect of the guidance strategy, a Monte Carlo simulation is performed to determine whether the contingency guidance successfully prevents violations. The Monte Carlo analysis is also used in the mission design to determine constant parameter values in the contingency objective.

## Session: Orbital Dynamics, Perturbations, and Stability

### Room: Topaz 1, Time: 08:00 AM-10:00 AM

Session Chair: Atri Dutta (Wichita State University)

08:00 AM **101: Advanced ensemble modeling method for space object state prediction accounting for uncertainty in atmospheric density**

*Smriti Nandan Paul*, Richard Licata and Piyush Mehta*

For objects in the LEO region, uncertainty in atmospheric density estimation is an important source of orbit prediction error. This paper investigates the evolution of orbit error distribution in the presence of atmospheric density uncertainties, which are modeled using probabilistic machine learning techniques. The investigation is convoluted because of the spatial and temporal correlation of the atmospheric density values. We develop several Monte Carlo methods, each capturing a different spatiotemporal density correlation. However, Monte Carlo analysis is computationally expensive, so a faster method based on the Kalman filtering technique for orbit uncertainty propagation is also explored.

08:20 AM **176: Large Eccentricity Growth at High Inclinations for Orbits at or near GEO Altitudes**

*Chia-Chun Chao**

A recent numerical study by the author revealed a large eccentricity growth of GEO at critical inclination and higher. As the inclination is increased to 76 deg, the eccentricity exponentially grows to 0.84 with perigee height approaching zero in less than 80 years. Through analytical investigation with doubly-averaged equations, the coupling between the de/dt and d?/dt equations caused by $J_2$ and third-body attractions appears responsible for the large eccentricity growth. Those simplified equations reduced from the averaged equations reveal the sensitivity of the large eccentricity growth to the initial values of right ascension of ascending node and argument of perigee.

**08:40 AM** **189: Backbone of ballistic capture set**

*Gianmario Merisio* and Francesco Topputo*

Currently, deep-space missions strongly rely on ground-based operations. Although reliable, ground slots will saturate soon, hampering current momentum in space exploration. EXTREMA, a project awarded an ERC Consolidator Grant in 2019, enables self-driving spacecraft, challenging the current paradigm and aiming at autonomously engineering ballistic capture. Deep-space GNC applied in a complex scenario is its subject. The paper defines the backbone of a ballistic capture set and presents a methodology based on Lagrangian descriptors for its derivation. Orbits belonging to capture sets up to $C_{-1}^{10}$ are inferred from the backbone. The method constitutes a block of the autonomous ballistic capture algorithm.

**09:00 AM** **192: A second-order closed-form J2 short-period motion model for the Draper Semi-analytical Satellite Theory**

*Juan Félix San-Juan*, Rosario López, Miguel Alonso and Paul J. Cefola*

In a previous paper, perturbation theory was applied to derive in an analytic way the second-order closed-form J2 model for the mean element equations of motion consistent with DSST. The perturbation method was carried out using the extended Lie-Deprit method and supported by MatATESAT, a Mathematica-based package. Following the same process, in this paper, we derive the osculating-to-mean and mean-to-osculating transformations and integrate them into the C/C++ version of the Draper Semi-analytical Theory. The mean to-osculating expressions are validated with existing ones based on the power series of eccentricity. Numerical examples are given.

**09:20 AM** **245: Characterizing the coupling mode of dynamics and deformation of an irregularly shaped, self-gravitating body: Application to the martian satellite, Phobos**

*Masatoshi Hirabayashi**

When an irregularly shaped, self-gravitating body orbits a massive planetary body, the dynamical behavior of such a body becomes complex due to the coupling of dynamics and deformation. Because the classical rigid-body dynamics do not account for deformation, characterizing the dynamics of a deforming body requires careful assessments. In this study, efforts are introduced to (1) offer an approach applying finite element modeling (FEM) to characterize the dynamics of a self-gravitating, deforming body experiencing a strong tidal effect and (2) apply it to the dynamics of the martian moon, Phobos.

**09:40 AM** **248: Extensive Search of Ballistic Capture Trajectories in the Circular Restricted Three Body Problem**

*Lorenzo Anoè*, Claudio Bombardelli and Roberto Armellin*

Obtaining the full set of initial conditions leading to a ballistic capture in the CRTBP is a challenging and computationally demanding task. Here, we propose a new method which hinges on the evolution of the two-body energy transition domain (ETD), i.e. the region where the capture osculating orbit around the second primary switches from hyperbolic to elliptic. An extensive analysis conducted for different values of the Jacobi constant and the primary mass ratio indicates that the evolution of the ETD follows a predictable pattern, remains rather compact in shape and bounded in a small region. Many interesting aspects of the capture mechanism are investigated exploiting this computationally efficient method.

# Session: Spacecraft Autonomy

**Room: Topaz 3, Time: 08:00 AM-10:00 AM**

Session Chair: Keith LeGrand (Purdue University)

**08:00 AM**

### 116: A Comparison of Deep Reinforcement Learning Algorithms for Earth-Observing Satellite Scheduling

*Adam Herrmann*, Hanspeter Schaub and Scott McKinley*

Deep reinforcement learning (DRL) has shown promise for on-board planning and scheduling, particularly for Earth-observing satellites (EOS). However, the question of which DRL algorithms are best suited for EOS scheduling problems has not been comprehensively explored. This work compares several state-of-the-art reinforcement learning algorithms for EOS scheduling. Shielded and unshielded value-based and policy gradient DRL algorithms are applied to the problem and compared on the basis of performance, sample efficiency, and model complexity. Policy gradient methods are shown to produce the highest performing policies for the smallest number of trainable network parameters.

**08:20 AM**

### 155: Design and Validation of Spacecraft Planning Flight Software

*Timothy Woodbury*, Austin Probe, Robert Effinger, Jose Rosales and Cheryl Gramling*

Various current and future civil, commercial, and defense space missions rely on cooperating groups of vehicles. Onboard autonomy can benefit these missions by reducing the need for ground-based commanding. One application of autonomy is onboard planning, which can augment ground-based planning and enable opportunistic data collection and remote operation. This paper presents the development of an initial proof-of-concept planning pipeline, which is validated in a Lunar communications and navigation mission with four cooperating vehicles. Results include representative schedules and simulated state histories. Subsequently, the original design is reviewed and extended to support a flight software prototype.

**08:40 AM**

### 174: Development of a simulator for coverage planning of a 6G/IoT constellation

*Franco Criscola*, David Canales Garcia, Joan Adria Ruiz-de-Azua Ortega, Arnau Singla, Anna Calveras and Elena Ponce*

New 6G/IoT technologies have brought forward countless new challenges for telecommunication providers. A main challenge is integrating this innovation to present systems and networks, and so companies have found solutions in lowEarth orbit constellations and non-terrestrial networks that substantially decrease latency but raise problems like how to manage a large constellation. The objective of this paper is to present a solution and showcase a simulator that can accurately predict locations of dozens of satellites. The result of this simulation is a precise computation of windows of coverage for events like Sun-charging, ground station communication, and target area communication.

**09:00 AM**

**205: Towards 6G Non-Terrestrial Networks - An Autonomous Constellation Management Engine**

*Arnau Singla*, Franco Criscola, Elena Ponce, David Canales Garcia, Anna Calveras and Joan Adria Ruiz-de-Azua Ortega*

The mobile communications industry is nowadays trying to integrate non-terrestrial and satellite networks into its traditional architecture. For the case of a satellite-based Non-Terrestrial Network (NTN), traditional operations for satellite planning cannot be applied due to this new heavily constrained scenario. This paper presents the motivation to deploy a Low Earth Orbit (LEO) NTN for 6G/IoT purposes, and the need of automating the operations management using Artificial Intelligence (AI) technologies. It then describes i2CAT's own designed management tool proposed as solution for an unaddressed use case in the literature along with the results obtained using a prototype of this management tool with a modeled real scenario.

**09:20 AM**

**259: Autonomous Lidar-free Hazard Detection and Landing Site Selection for Small Bodies Descent**

*Edoardo Caroselli*, Maurice Martin, Karl Atkinson, Fabio Curti and Roger Foerstner*

The micro-lander architecture defined in the framework of the NEO-MAPP study allows an autonomous and safe soft landing on asteroid surface. In this paper an autonomous LiDAR-free hazard detection system is presented enabling safe landing site selection on-board based on given landing requirements.
The novel solution presented efficiently includes machine learning-based (ML) functionalities with traditional image processing (IP) in a hybrid workflow. Standard approaches make extensive use of heavier LiDAR information processing, which in our mission is not compatible with stringent mass requirements of NEO-MAPP µLander architecture.
Its application is not only limited to SSSBs surface but it can be also employed on planetary landing.

## Session: Trajectory/Mission/Maneuver Design and Optimization 4

**Room: Topaz 2, Time: 08:00 AM-10:00 AM**

Session Chair: Nicholas Bradley (NASA / CalTech - JPL)

**08:00 AM**

**421: Minimum-Time, Low-Thrust Earth-to-Moon Transfers Using Adaptive Gaussian Quadrature Collocation**

*George III Haman* and Anil Rao*

The problem of minimizing the transfer time from an Earth orbit to a lunar orbit using low-thrust propulsion is considered, where the motion of the spacecraft is governed by the dynamics of the circular and elliptic restricted three-body problems. The spacecraft's thrust magnitude is constrained to its maximum value; therefore, the spacecraft's final mass is maximized. The continuous-time optimal control problem is discretized using a direct, adaptive Legendre-Gauss-Radau quadrature collocation method and transformed into a large, sparse nonlinear programming problem. It is shown that the problem formulation and results obtained in this investigation improve the transfer time relative to prior work on minimum-time Earth-to-Moon transfers obtained via indirect shooting.

**08:20 AM**

### 291: Impact of Different Coordinate Sets on the Performance of Convex Low-Thrust Trajectory Optimization

*Christian Hofmann, Andrea Carlo Morelli* and Francesco Topputo*

The choice of the coordinate representation of the dynamics has a considerable impact on the performance of low-thrust trajectory optimization methods. Especially the convergence of convex programming techniques can suffer from a poor choice due to the successive linearization of nonlinear dynamics. Despite the rising popularity of convex optimization, no work has investigated the role of different coordinate sets yet. In this paper, we assess various coordinate representations for the low-thrust trajectory optimization problem. We consider standard (e.g. Cartesian, spherical, equinoctial elements), and also introduce non-standard coordinates (e.g. Kustaanheimo-Stiefel, modified orbital elements) that result in linear dynamics in the unperturbed case.

**08:40 AM**

### 315: Smooth Enforcement of Forced-Coasting Arcs for Various Low-Thrust Transfer Mission Requirements

*Nicholas Nurre* and Ehsan Taheri*

Modeling events such as electric-propulsion duty cycle or the occurrence of eclipses as forced-coasting constraints within an indirect-based trajectory optimization method can be difficult due to the discontinuities introduced in the spacecraft dynamics. We present an indirect-based framework for smoothly enforcing discrete forced-coasting constraints without the need for deriving additional necessary optimality conditions. Forced-coasting constraints are smoothly enforced at the level of the Hamiltonian using a Composite Smooth Control (CSC) method. Minimum-time and minimum-fuel low-thrust trajectory optimization problems with different forced-coasting constraints are solved. Results indicate that high-resolution forced-coast-conscious fuel- and time-optimal trajectories can be generated.

**09:00 AM**

### 149: Invariant Manifold Approximations in the Circular Restricted Three-Body Problem with Applications to Low-Thrust Trajectory Design

*Patrick Kelly*, John L. Junkins and Manoranjan Majji*

In this paper methods to parameterize and approximate the hyperbolic invariant manifolds of particular solutions in the Circular Restricted Three-Body Problem (CR3BP) are presented. A multivariate Chebyshev series is used to deliver highly precise approximations of these surfaces. It is demonstrated that the continuum of ballistic capture trajectories and their associated sensitivities on the manifold can be realized in functional form to nearly integrator tolerance using simple algebraic operations and a reasonably small set of coefficients. Applications of this result to low-thrust trajectory optimization and spacecraft guidance in multi-body regimes are presented.

**09:20 AM** **255: Design of Initial Guess Low Thrust Trajectories Using Clohessy-Wiltshire Equations**

*Madhusudan Vijayakumar*, William Skamser and Ossama Abdelkhalik*

Design and optimization of low thrust space trajectories is a complex and computationally intense process. dditionally, the optimal solvers used to generate these trajectories are extremely sensitive to initial guesses. One way to overcome this challenge is to use a reasonably approximate trajectory as an initial guess on optimal solvers. This paper presents a flexible semi-analyticapproach in generating planar and three-dimensional initial guess trajectories for various design scenarios like orbit raising, orbit insertion, phasing, and rendezvous. NASA's Evolutionary Mission Trajectory Generator (EMTG) and General Mission Analysis Tool (GMAT) are used as optimal solvers in this analysis. Numerical case studies are presented in this paper.

**09:40 AM** **128: Low-Thrust Resonance Gravity Assist Trajectory Design to the Moon**

*Jinsung Lee* and Jaemyung Ahn*

We propose a low-thrust resonance gravity assist trajectory design and optimization procedure for producing an optimal propellant mass transfer to the Moon using the circular restricted three-body problem. Multiple resonance sequences were tested with different Jacobi integrals to validate the trajectory design and optimization procedure. The resonance gravity assist was integrated with the Q-law guidance algorithm to design a trajectory for spacecraft ridesharing to Geo-transfer orbit.

## Session: Machine Learning and Artificial Intelligence Applied to Space Flight Problems 1

**Room: Onyx 2-3, Time: 10:20 AM-12:00 PM**

Session Chair: Hang Woon Lee (West Virginia University)

**10:20 AM** **158: The Physics-Informed Neural Network Gravity Model Revisited -- Model Generation III**

*John Martin* and Hanspeter Schaub*

Many analytic gravity models carry undesierable assumptions, computational constraints, or memory burdens to space-flight. The physics-informed neural network gravity model (PINN-GM) offers a compelling alternative to these past models by learning, rather than prescribing, convienent basis functions to represent unique gravitational environments. This paper will explore the most recent developments of the PINN-GM (Generation 3) and will compare the performance of the new model against past generations in the Earth, Moon, and Eros systems.

**10:40 AM** **168: A Machine Learning Model for Solar Sail Shape Reconstruction Using Flight Data**

*Ryan Wu*, Sanjog Gururaj and Daniel Tyler*

Solar sail deformation leads to disturbance torques from solar radiation pressure, driving performance requirements for momentum management systems. We have developed a model leveraging neural network-based machine learning to derive sail shape characteristics. Using simulated torque and attitude telemetry, it predicts boom deflection, center of mass deviation, and other shape metrics with comparable accuracy to that of an onboard context camera. This model can validate sail shape models and predict disturbances with no additional mass or data downlink requirements, holding promise for the further implementation of machine learning techniques in solar sail telemetry analysis and control.

**11:00 AM** **221: Adaptive Optimal Output Regulation of Autonomous Satellite Docking: A Reinforcement Learning Approach**

*Omar Qasem*, Madhur Tiwari and Hector Gutierrez*

This paper describes an off-policy data-driven reinforcement learning-based algorithm to regulate and control the relative position of a deputy satellite in an autonomous satellite docking problem under the framework of output regulation and adaptive dynamic programming problems. The optimal control problem is presented using a data-driven reinforcement learning-based method to regulate the relative position/velocity of the deputy to safely dock with the chief. Using the adaptive optimal output regulation framework, the learned feedback-feedforward gains guarantee optimal transient and steady state performances. Reference tracking and disturbance rejection are achieved in an optimal sense without any information of the physics of the satellites.

**11:20 AM** **232: Artificial Intelligent Tactile Feedback Control for Autonomous Robotic Capture of Non-Cooperative Space Target**

*Bahador Beigomi and George Zhu**

## Session: Orbital Dynamics, Perturbations, and Stability

**Room: Topaz 1, Time: 10:20 AM-12:00 PM**

Session Chair: Atri Dutta (Wichita State University)

**10:20 AM** **262: Preliminary Study Of The Earth Perturbation Over Low-Thrust Trajectories**

*Josué Cardoso dos Santos*, Takuto Shimazaki and Yasuhiro Kawakatsu*

This work intends to model the type of dynamics under which the spiral trajectory phase of the DESTINY+ mission will evolve considering gravitaty perturbations from Earth. The type of trajectory involved in this phase of the mission deal with the continuous raising altitude low-thrust trajectory which will depart from the Earth towards the Moon. After a lunar approach, the trajectory will be redirected by a gravity assist towards a flyby with the asteroid 3200 Phaeton. Some disturbing forces need to be accounted for the spiral phase, namely the flattening at Earth's poles. The modelling of this dynamics prepares for faster (averaged/close) solutions for the optimization algorithms used by the mission.

*Grigory Nikitin* and Kyle T. Alfriend*

The Moon's $J_2$ coefficient is the same order of magnitude as many other relevant gravitational coefficients. Because of that Brouwer's orbit theory cannot be applied for the Moon. Mahajan resolved this issue with implementing the lunar analytic orbit theory. The purpose of this paper is to determine the effects of the short and long period terms in the Kepler elements and to compare the accuracy of the lunar analytic orbit theory with the numerical method of propagation. It is important to know the orbits and altitudes for which this theory can be applied without losing much accuracy.

**11:00 AM** **349: A Global Method to Compute Asteroid Equilibrium Points for Any Spin Rate**

*Gavin Brown* and Daniel Scheeres*

A method was developed to compute all possible equilibria that could exist in the vicinity of a uniformly rotating body at all possible spin rates. This method improves on other techniques currently used that involve computing the ridge line. Several asteroids with a variety of shapes were used to test the validity of this method, including Bennu, Betulia, and Eros. While it is difficult to know how many equilibria could exist for a system a priori, the results obtained using this method matched previous results for the equilibria of Bennu obtained using the computation of the ridge line.

**11:20 AM** **385: REGULARIZED CANONICAL COORDINATES FOR CENTRAL FORCE MOTION**

*Joseph Peterson*, Manoranjan Majji and John L. Junkins*

A point transformation for projective coordinates is lifted to a canonical transformation in extended and over-parameterized phase space. This is a regularizing canonical transformation that fully linearizes the unperturbed Kepler problem, leading to a closed-form solution and a new set of eight canonical orbit elements. A subsequent canonical transformation from these projective coordinates to new quaternionic canonical coordinates is then constructed. The Hamiltonian system in the quaternionic coordinates closely resembles that of the Kustaanheima-Stiefel coordinates, but with two extra dimensions which allow for decoupling of the radial and rotational motion.

# Session: Spacecraft Autonomy

## Room: Topaz 3, Time: 10:20 AM-12:00 PM

Session Chair: Keith LeGrand (Purdue University)

**10:20 AM** **285: Development of 6DOF hardware-in-the-loop ground testbed with active gravity compensation by dual robotic manipulators**

*Ahmad Al Ali and George Zhu**

Capturing non-cooperative targets using autonomous robotic manipulators presents a set of unique and exciting challenges, not the least of which is the autonomy problem. The current research gap is that the existing studies are primarily theoretical and are ob-tained by computer simulation. However, before these results can be used in an actual space mission, they must be validated experimentally in a microgravity environment, which is difficult to achieve. In this paper, we describe our effort to design and build a ground testing facility and how it can be used for testing the control algorithms for the robotic capture of a non-collaborative target.

**10:40 AM** **334: Global Task-Aware Fault Detection and Identification For On Orbit Multi-Spacecraft Collaborative Inspection**

*Akshita Gupta, Yashwanth kumar Nakka, Changrak Choi and Amir Rahmani**

In this paper, we present a global-to-local task-aware fault detection and identification (GLT-FDI) algorithm to detect failures in a multi-spacecraft system performing a collaborative inspection (global) task. The inspection task is encoded in a cost H that informs global autonomy (task allocation and assignment) and local (agent-level) autonomy. The metric is a function of the inspection sensor model, and the agent full-pose. We use the cost function H to design a metric that compares the expected and actual performance to detect the faulty agent using a threshold and identify the fault type. We demonstrate it on a low-Earth orbit mission.

**11:00 AM** **188: SPESI: a real-time Space Environment Simulator for the EXTREMA project**

*Carmine Giordano* and Francesco Topputo*

EXTREMA is a project, funded by the European Research Council, that aims towards a paradigm shift in the spacecraft Guidance, Navigation, and Control, by enabling probes able to reach their destination in a totally autonomous fashion. Within the project, the EXTREMA Simulation Hub will be exploited to carry on dynamic simulations of the spacecraft-environment interaction, allowing high-fidelity testing of deep-space autonomous GNC systems. This work presents the EXTREMA's space environment simulator (SPESI). SPESI has the aim to propagate forward the spacecraft trajectory and generate the surrounding scene to be fed by the spacecraft sensors in real time.

**11:20 AM** **394: Orbit Management During Solar Cycle 25 for Optimal Science on GRACE-FO Mission**

*Himanshu Save*, John Ries, Srinivas Bettadpur, Peter Nagel and Nadege Pie*

GRACE-FO mission makes global measurements of the surface mass changes over the Earth. Due to the failure of a critical instrument on one of the two spacecrafts, the error in the science products from the mission increases with increasing drag. With the onset of the solar cycle 25, the project needs to manage orbit raises to reduce the effective drag and in turn reduce these errors. We discuss the studies performed to devise an orbit management strategy to optimally use the limited amount of fuel for orbit raising while achieving best possible science goals under the operational constraints.

**11:40 AM** **343: A Method to Autonomously Detect a Client Point Source During Angles-Only Navigation**

*Samuel Laurila and Mark Muktoyuk**

Angles-Only Navigation (AON) is an important navigation technique used in satellite rendezvous that involves a servicer spacecraft imaging a client spacecraft. When imaged from afar, the client spacecraft can appear as a point source. The client must be distinguished from any other light source or noise on the focal plane for an accurate angle measurement. An autonomous method to determine which pixels are the client has been developed for the first phase of the Japan Aerospace Exploration Agency (JAXA) Commercial Removal of Debris Demonstration (CRD2-1). Astroscale is the commercial partner for CRD2-1 and is developing the Active Debris Removal by Astroscale-Japan (ADRAS-J) satellite. The underlying reasoning of this method will be discussed.

## Session: Trajectory/Mission/Maneuver Design and Optimization 4

**Room: Topaz 2, Time: 10:20 AM-12:00 PM**

Session Chair: Nicholas Bradley (NASA / CalTech - JPL)

**10:20 AM** **283: Overburn and Underburn Analysis for NASA's Solar Cruiser Mission**

*Jared Sikes*, Ari Rubinsztejn, James Pezent, Rohan Sood, Jason Everett and Andrew Heaton*

In this work, trajectory analysis for NASA's Solar Cruiser mission for launch vehicle injection errors was performed. Cold dispersions are shown to be difficult to re-converge to the nominal mission orbit, requiring the use of an alternate heliocentric trajectory profile to
satisfy mission requirements. A mapping of successful escape trajectories is shown, where achieving the desired heliocentric escape is highly dependent on the solar sail deployment date. In contrast, hot injections are demonstrated to have a near 100% re-convergence rate to
the initial mission orbit, at the expense of added time of flight.

**10:40 AM**

**310: Artificial Neural Network based Atmospheric Density Model for Aerobraking Trajectory Design**

*Amrutha Dasyam* and Atri Dutta*

This paper considers the trajectory design of an aerobraking maneuver in which a spacecraft makes multiple atmospheric passages to decelerate to a low-altitude circular orbit. While accurate estimates of atmospheric density are important for aerobraking maneuver design, direct incorporation of high-fidelity atmospheric density models into the design framework require more computational resources. In this paper, we propose a neural network-based methodology to approximate a high-fidelity atmospheric density model for aerobraking maneuver design. We compare the acquired aerobraking trajectories with the trajectories generated based on exponential density model from the literature.

**11:00 AM**

**216: Assessment of Aerogravity Assist at Venus Using Blunt-Body Vehicles**

*Daniel Engel*, Rahil Makadia and Zachary Putnam*

Aerogravity assist options using a blunt-body aeroshell for Venus are considered in this study. Parameter sweeps over ballistic coefficient, lift-to-drag ratio, and bank angle for a blunt body entry vehicle are evaluated for various performance characteristics, such as turn angle and heliocentric velocity change. Results show that aerogravity assists with blunt bodies at Venus may provide performance enhancements over conventional gravity assists over a range of initial flight-path angles and ballistic coefficients. In particular, turn angles of over 95 deg and heliocentric velocity changes over 8 km/s are possible.

**11:20 AM**

**284: Mission Design for Near-Future Solar Polar Imaging Mission Leveraging Venus Flyby**

*James Pezent*, Rohan Sood, Andrew Heaton and Les Johnson*

In this work we examine mission design for near future solar polar imaging (SPI) missions leveraging solar sails. Specifically, we investigate whether including a Venus flyby can improve overall mission time of flight compared to a traditional SPI mission architecture. For both the flyby and non-flyby architectures, time optimal transfers are computed to a 75-degree inclination science orbit at 0.48 AU across a range of feasible Earth departure velocities, cranking radii, and sail sizes. Preliminary results suggest that including a Venus flyby reduces overall mission time of flight by 12-17% compared to the traditional mission architecture.

**11:40 AM**

**115: Overview of the NASA Spacecraft Trade Modeling System (NSTRDMS), A Rapid Mission Analysis Tool**

*Scott Karn*, Steven McCarty, Melissa McGuire and Rutvik Marathe*

A rapid mission analysis tool is developed to support the ongoing design of a Lunar Transit trajectory of the Power and Propulsion Element (PPE) between a Medium Earth Orbit (MEO) parking orbit and a lunar L2 southern Near Rectilinear Halo Orbit (NRHO). A parameterization is developed by which the Lunar Transit can be analyzed in the context of varying vehicle mass, solar electric propulsion (SEP) configurations, and solar array power output. A rapid and novel mission analysis tool enables a wide array of these trade analyses to be completed without the need for extensive computing resources or time.

## Session: Machine Learning and Artificial Intelligence Applied to Space Flight Problems 2

**Room: Topaz 1, Time: 01:30 PM-03:10 PM**

Session Chair: Davide Amato (Imperial College London) and Davide Guzzetti (Auburn University)

**01:30 PM** **241: Enabling Machine Learning Inference at the Edge**

*Brett Carver*, Austin Probe and Timothy Esposito*

State-of-the-art Machine Learning (ML) often utilizes neural networks to perform complex tasks, which can be challenging to execute on-orbit due to hardware resource constraints. To overcome resource constraints, we propose an ML-Accelerated Grid Environment (MAGE). MAGE?is a?software framework and API that facilitates ML training and inference?distributed?across a?networked?constellation or swarm of satellites. We identify two distribution strategies, model distribution and data distribution, to effectively distribute resource load. Through a NASA research contract, we performed a feasibility analysis on model distribution to distribute the resource load of a U-Net neural network across multiple spacecraft to achieve a nearly 80% reduction in RAM utilization per-spacecraft.

**01:50 PM** **247: Reinforced Lyapunov Controllers and Convex Optimisation for Low-thrust Lunar Transfers**

*Harry Holt, Nicolò Bernardini*, Nicola Baresi and Roberto Armellin*

Future missions to the Moon and beyond are likely to involve low-thrust propulsion technologies due to their superior propellant efficiency. However, these still present a difficult trajectory design problem. In this work a Reinforced Lyapunov Controller is used in conjunction with convex optimisation to design optimal low-thrust transfers from GTO towards low-altitude lunar orbits. A dual-actor network setup is used, one in each of the Earth- and Moon-centred inertial frames respectively. One of the major challenges involves patching these two legs together. In this paper, convex optimisation and sliding patching points help alleviate these issues, particularly in regions where the two-body model is a poor approximation of the CRTBP dynamics.

**02:10 PM** **278: Transformer-based anomaly detection on dynamic graphs: application to satellite constellations**

*Manuel Indaco* and Davide Guzzetti*

While society benefits from the high-quality services provided by emerging P-LEO constellations, such large space systems are difficult to monitor due to system size, complexity, and dynamic structure. In this work, we investigate the problem of anomaly detection on non-terrestrial networks (NTNs). First, we transform a NTN system into a dynamic graph; next, we employ a transformer-encoder neural network to identify anomalous links. Early results for a simplified, centralized scenario demonstrate the effectiveness of the method, encouraging further investigation to achieve on-edge anomaly detection.

**02:30 PM** **294: Deep Monocular Hazard Detection for Safe Small Body Landing**

*Travis Driver, Kento Tomita*, Koki Ho and Panagiotis Tsiotras*

Hazard detection and avoidance is a key technology for future robotic small body sample return and lander missions.
Current state-of-the-practice methods rely on high-fidelity *a priori* terrain maps, which require extensive human-in-the-loop verification and expensive reconnaissance campaigns to resolve mapping uncertainties. We propose a novel safety mapping paradigm that leverages deep semantic segmentation techniques to predict landing safety maps directly from monocular images, thus reducing reliance on high-fidelity *a priori* data products. We demonstrate state-of-the-art safety mapping performance on real reconnaissance imagery of a prospective sample site from the OSIRIS-REx mission.

**02:50 PM** **306: Space Inspection For CubeSats And Other Space Targets Using Object Detection In Images**

*Anh Nguyen* and Donghoon Kim*

As space debris and satellites increase, they start posing threats to space missions. Therefore, it's necessary to increase the situational awareness capability of satellites. Thus, having an accurate, fast, and lightweight computer vision model deployed on board spacecraft to inspect space for space targets is valuable. Since the biggest challenge to training such a supervised model is the lack of real data, we designed a blender pipeline to generate, customize, and randomize images of space targets with space backgrounds and demonstrated that a real-time state-of-the-art object detection model can be trained to detect and differentiate CubeSats and other space targets.

## Session: Orbit Determination and Space Surveillance Tracking 2

**Room: Onyx 2-3, Time: 01:30 PM-03:10 PM**

Session Chair: Christopher Roscoe (Ten One Aerospace)

**01:30 PM** **267: MIXTURE-BASED COST METRICS FOR MANEUVER DETECTION USING RADAR TRACK DATA**

*Jose M. Montilla, Rafael Vazquez* and Pierluigi Di Lizia*

In Space Situational Awareness, maneuver detection is key given that frequently satellites perform unpublished maneuvers. Two proposed metrics for anomaly detection are presented, based on measurements from a single surveillance radar. Since few observations are available, long propagations require realistic uncertainty representation, which is tackled with Gaussian-mixtures. The propagated state is compared with the track data to compute a cost metric from the literature, similar to the Mahalanobis Distance; the variation of this metric along the track is used to define a novel, second metric. Preliminary results show promise, improving the classical MD at maneuver detection and avoiding false positives.

**01:50 PM**

### 272: Nonlinear Kalman Filter Based On Central Differences Applied To Orbit Determination Problem

*Helio Koiti Kuga*, Roberta V. Garcia, Paula C P M Pardal, William R. Silva, Maria Zanardi and Leandro Baroni*

This work presents the nonlinear Kalman Filter (KF) based on Central Differences (CD) as a solution for nonlinear problems of estimation, which avoids calculation of partial derivatives matrices appearing when Extended Kalman Filter (EKF) is applied. In Orbit Determination (OD) nonlinearities are present in both orbit dynamics and measurement processes. In EKF linearizarion process the appearing partial derivative matrices (Jacobians) must be computed. Herein the Jacobians are not computed but rather approximated via Central Differences, giving rise to the derivative-free Central Difference Kalman Filter (CDKF). The CDKF will be applied to a OD problem where numerical simulations are carried out to show assets and drawbacks of CDKF as compared to conventional EKF.

**02:10 PM**

### 280: Orbit Determination via Eclipse Transient Timing: Improved Methods and Intensity Models

*Riley Fitzgerald* and Truman DeWalch*

As small spacecraft become more prevalent, there is increased need for autonomous orbit determination (OD) methods requiring minimal input and hardware. Previous work demonstrated OD using only observations of eclipse duration and transient shape parsed from measurements of sunlight intensity. These methods rely on penumbra models accounting for Earth's atmosphere and oblateness. We present improved models of—and corrections for—the eclipse transients, and quantify uncertainty in transient location and shape due to time- and space-varying refractivity, absorption, and topography. Finally, we show how these are incorporated into the estimation pipeline, and validate OD performance against publicly-available TLE data.

**02:30 PM**

### 300: A novel fast-paced orbit determination method for the Cnes catalogue

*Emmanuel Delande*, Florian Thuillet, Pascal Richard, Valentin Baral and Manuel Pavy*

This paper presents a novel orbit determination (OD) tool for the CNES catalogue. It relies on a traditional least-square method, but adopts a sequential flow in which the covariance of the input track is leveraged and the observation arcs of successive OD steps are non-overlapping. Short-scale tracks aim to detect maneuvers and cut observation arcs accordingly, while long-scale tracks are generated afterwards to deliver smoother trajectories between identified maneuvers. Overall, the new OD tool proves more reactive and flexible in the presence of maneuvers, more stable in the estimation of the SRP term in challenging scenarios, and computationally faster than an OD tool using sliding, overlapping observation arcs.

**02:50 PM**

### 304: THE INITIAL ORBIT DETERMINATION (IOD) PROBLEM WITH RANGE, RANGE-RATE AND ANGLES

*Christopher DSouza* and Renato Zanetti*

An analytical formulation of the Initial Orbit Determination (IOD) problem for range, range-rate and angle measurements. This approach involves the use of the Lagrange interpolating polynomials to obtain the position and velocity estimate. In addition the covariance matrix associated with the state estimate is provided.

# Session: Spacecraft Guidance, Navigation and Control 3

## Room: Topaz 3, Time: 01:30 PM-03:10 PM

Session Chair: Casey Heidrich (University of Colorado Boulder)

**01:30 PM**

**339: Decentralized predictive guidance and control for formation flying of NASA astrobee robots**

*Isuru Basnayake, John Martinez* and Hyeongjun Park*

Astrobees are free-flying autonomous robots becoming useful in offloading repetitive and simple routines necessary for the monitoring and maintenance of the International Space Station. They are the cornerstone of automated space explorations as the capability of working as a group becomes a critical role. In this paper, we propose a decentralized model predictive control framework accommodating dynamic formation control. The proposed framework guarantees to generate collision-free trajectories using approaches for an exclusive region obstacle avoidance and safe maneuvering around constrained environments. The simulation results demonstrate the efficacy of the framework with two different scenarios from one module to another.

**01:50 PM**

**356: Powered Descent Guidance and Control for the Blue Ghost Lunar Lander**

*Adam Licavoli*, Michael Barrucco, James Kaidy and Scott Yantek*

Presented are a set of guidance laws and control structures adapted for the Blue Ghost lunar lander, a commercial lander built by Firefly Aerospace. This guidance and control architecture is designed to perform an efficient, robust, and stable powered descent. This paper provides a detailed look into the algorithms that will be used to perform a soft landing in Mare Crisium in 2024. With the proposed design, we are able to achieve landing accuracies within 15 meters relative to navigated states. Time and frequency domain simulation results are provided to substantiate these claims.

**02:10 PM**

**370: Nonlinear Filtering with Intrusive Polynomial Chaos for Satellite Uncertainty Quantification**

*Z McLaughlin*, Brandon Jones and Renato Zanetti*

Propagating and quantifying the uncertainty associated with a Anthropogenic Space Object (ASO) is necessary for many space organizations and government entities to facilitate object tracking and spacecraft nagivation in uncertain environments. As the scope of activity in space grows, so does demand for filtering technologies able to handle chaotic and uncertain systems. This work presents a filter leveraging intrusive Polynomial Chaos Expansions (PCEs) to track an object's probability distribution even as it becomes non-Gaussian in environments with scarce measurements, high a priori uncertainty, and chaotic dynamics. The following discussion covers bakground on PCEs and polynomial filtering and comparison to sampling methods and popular filters used in astrodynamics.

**02:30 PM** **340: Computationally-Efficient Sequential Visual-Inertial SLAM for Asteroid-Relative Navigation**

*Matthew Givens*, Jacopo Villa and Jay McMahon*

Small body exploration presents many distinct challenges for spacecraft navigation including the potential for large initial ephemeris errors, large uncertainties in the gravitational environment, and rapidly-varying lighting conditions. Here, we apply an algorithm to perform Simultaneous Localization and Mapping of an asteroid by utilizing information from an onboard camera and IMU. While the accelerometers cannot sense the gravitational forces at play, they do provide real-time information on any maneuvers that the spacecraft performs and thus can be utilized to help disambiguate the scale of visual features. A sequential VI-SLAM algorithm, IIPA-SLAM, is described and demonstrated with synthetic imagery of an asteroid and a representative trajectory.

**02:50 PM** **368: Revisiting Analytical Solution for the Gravity-Turn Guidance Law**

*Bharat Mahajan**

Gravity-turn is a widely used guidance law for planetary/lunar descent/ascent trajectories. It is easy to implement and can be shown to provide a close approximation to the optimal trajectory. The pure gravity-turn guidance law is amenable to analytical solutions if a few simplifying assumptions are used in the equations of motion. The classical closed-form solution for the gravity-turn guidance breaks down for descent if the initial velocity is greater than the circular orbital speed at zero altitude. In this work, a new series solution for the gravity-turn guidance is presented that is applicable for descent/ascent from/to low-to-mid altitude elliptical orbits.

## Session: Trajectory/Mission/Maneuver Design and Optimization 5

**Room: Topaz 2, Time: 01:30 PM-03:10 PM**

Session Chair: Jason Leonard (KinetX)

**01:30 PM** **208: A hybrid multiple-shooting approach for covariance control of interplanetary missions with navigation errors**

*Nicola Marmo*, Alessandro Zavoli, Naoya Ozaki and Yasuhiro Kawakatsu*

Several sources of stochastic disturbances and dynamical uncertainties may critically deviate a spacecraft from a nominal optimal trajectory. This manuscript proposes a systematic robust trajectory design method, where quantitative information concerning uncertainty on the system dynamics and stochastic navigation errors are directly accounted for in the optimization process. More precisely, a linear feedback control law is sought in order to steer the probability distribution of the spacecraft state towards a target distribution at an assigned final time. The proposed approach is applied on a portion of the future JAXA mission DESTINY+ with promising results.

**01:50 PM** **344: Preliminary Sequencing Method for Multiple Gravity Assists with Low-Thrust Synergetic Maneuvers**

*Ghanghoon Paik* and Robert Melton*

In order to design a trajectory for a mission with multiple planetary visits, generating sequences with proper timing is required. In addition to accounting for the planet's motion, the spacecraft has to meet strict conditions to perform gravity assist maneuvers around multiple planets. Algorithms are considered to determine optimal paths including low-thrust synergetic gravity assist between Earth and a terminal planet. In this paper, development of sequencing methods to design multi-purpose missions, i.e. number of planets to visit or minimize time/fuel to complete a mission, is addressed.

**02:10 PM** **325: Optimal Trajectory Generation for Rigid Body Landing Dynamics on the Special Euclidean Group**

*Brennan McCann* and Morad Nazari*

Rigid body trajectory optimization is becoming increasingly pertinent for landing missions. Formulating the rigid-body dynamics on special Euclidean group (SE(3)) mitigates singularity and nonuniquness issues of attitude parameterization sets and exploits the Lie group structure to compactly describe the motion. To perform the optimization problem using these dynamics, classical methods for optimization must be generalized to Riemannian manifolds and further extended to dynamic optimization problems. In this paper, the existing methods for optimization on Riemannian manifolds are used to provide a first-order gradient descent algorithm for optimizing the spacecraft landing problem on SE(3).

**02:30 PM** **182: Application of Local Lyapunov Exponents for NASA's Artemis-1 Trajectory Design and Maneuver Planning**

*Brennan Blumenthal* and Rohan Sood*

In this study, the use of Local Lyapunov Exponents (LLEs) are examined within the context of the Circular Restricted Three-Body Problem dynamical environment. NASA’s Artemis-1 mission is used as a baseline trajectory. LLEs are used in conjunction with a Two-Level Targeting differential corrections algorithm to alter the placement of impulsive maneuvers along the flight path, with the goal of reducing the overall ?V cost of the mission relative to the baseline trajectory.

**02:50 PM** **183: Application of Local Lyapunov Exponents for Autonomous Trajectory Targeting and Generation**

*Brennan Blumenthal* and Rohan Sood*

Local Lyapunov Exponents and Finite Time Lyapunov Exponents are used to autonomously generate, discretize, and target a feasible trajectory that achieves desired target states, given only a sparse set of target states as a starting point. LLEs are used to inform maneuver placement along a trajectory within the context of the Circular Restricted Three-Body Problem dynamical environment. LLE maneuver placement is then used in conjunction with a non-maneuver LLE-based patch point placement algorithm and an impulsive Two-Level Targeting algorithm to demonstrate an autonomous trajectory design and targeting process.

# Session: Machine Learning and Artificial Intelligence Applied to Space Flight Problems 2

**Room: Topaz 1, Time: 03:30 PM-04:50 PM**

Session Chair: Davide Amato (Imperial College London)

**03:30 PM**

**319: Laboratory Experimentation of Spacecraft Robotic Capture Using Deep Reinforcement Learning-based Guidance**

*Kirk Hovell and Steve Ulrich**

This paper considers a planar three-link manipulator-equipped spacecraft capturing and simultaneously stabilizing an uncooperative spinning target. Deep reinforcement learning is used to autonomously learn a real-time capture and simultaneous stabilization guidance strategy. The learned guidance strategy is trained entirely in simulation, where learning succeeds despite position, velocity, and acceleration constraints, randomized initial positions and target angular velocities, all while ensuring near-zero post-capture angular velocity. The trained guidance policy is transferred to a spacecraft platform in the Spacecraft Proximity Operations Testbed, an experimental facility at Carleton University, where a spinning target platform is captured and stabilized successfully despite being subjected to initial conditions and perturbations unseen in training.

**03:50 PM**

**391: Stochastic Hazard Detection For Landing Under Topographic Uncertainty**

*Kento Tomita* and Koki Ho*

Autonomous hazard detection and avoidance is a key technology for future landing missions in unknown surface conditions. Current state-of-the-art stochastic algorithms assume simple Gaussian measurement noise on dense, high-fidelity digital elevation maps, limiting the algorithm's applicability. This paper introduces a new stochastic hazard detection algorithm capable of more general topographic uncertainty by leveraging the Gaussian random field regression. The proposed approach enables the safety assessment with imperfect and sparse sensor measurements, which allows hazard detection operations under more diverse conditions. We demonstrate the performance of the proposed approach on the existing Mars digital terrain models.

**04:10 PM**

**423: Autonomous Rendezvous with Non-Cooperative Target Objects with Swarm Chasers and Observers**

*Trupti Mahendrakar*, Ryan White, Markus Wilde, Andrew Ekblad, Steven Holmberg and Emma Conti*

To aid the prevention of increasing space debris and assist with on-orbit servicing, this paper introduces the Multipurpose Autonomous Rendezvous Vision-Integrated Navigation system (MARVIN) developed and tested at the ORION Facility at the Florida Institution of Technology. MARVIN consists of two sub-systems: a machine vision-aided navigation system and an artificial potential field (APF) guidance algorithm which work together to command a swarm of chasers to rendezvous with the RSO safely. We present the MARVIN architecture and hardware-in-the-loop experiments demonstrating autonomous, collaborative swarm satellite operations successfully guiding three drones to rendezvous with a physical mockup of a non-cooperative satellite in motion.

## Session: Orbit Determination and Space Surveillance Tracking 2

**Room: Onyx 2-3, Time: 03:30 PM-04:50 PM**

Session Chair: Christopher Roscoe (Ten One Aerospace)

**03:30 PM**

**316: Approximate Minimum Divergence Filtering for Gaussian Initial Orbit Determination**

*Kyle Craft*, Kyle DeMars and Christopher D'Souza*

Accurate and statistically consistent initial orbit determination is crucial to the effectiveness of both spacecraft navigation and space domain awareness architectures. The use of a constrained admissible region has been shown to provide a robust prior estimate when no information is available a priori about the space object. However, when no admissible region is known to exist, e.g., cislunar space, orbit determination is typically limited to methods that incur linearization errors in addition to specific pitfalls. An initial orbit determination method is proposed by minimizing the Kullback-Leibler (KL) divergence between an approximate Gaussian probability density and the true Bayesian posterior.

**03:50 PM**

**346: An Extended Exploration of Angles-Only Initial Orbit Determination in Space-to-Space Earth-Orbiting Scenarios**

*Kenneth Horneman* and Alan Lovell*

This paper explores various methods of initial orbit determination for several space-to-space Earth-orbiting scenarios.Both classical methods in use for centuries and more modern methods are employed here. Both existing methods and new methods are evaluated for typically difficult space-to-space scenarios, such as co-planar target and observer, and highly elliptical motion. The results extend prior work for new scenarios with noisy measurement data. Examined methods include a hybrid Gauss/Laplace approach, Gooding and Double-R.

**04:30 PM**

**377: Multi-Fidelity Hamiltonian Monte Carlo for Space Object Tracking with Sparse Data**

*Enrico Zucchelli* and Brandon Jones*

This paper describes a method to combine multi-fidelity methods with Hamiltonian Monte Carlo for fast, efficient orbit determination in the case of very sparse data. Multi-fidelity methods combine high-fidelity models with low-fidelity models, allowing for fast propagation. Hamiltonian Monte Carlo methods are particle-based inference methods that sample directly from the posterior distribution; this fact makes this class of methods much more efficient than vanilla particle filters. Hamiltonian Monte Carlo exploits the gradient of the posterior and Hamiltonian dynamics to sample more efficiently than methods such as Markov Chain Monte Carlo.

## Session: Trajectory/Mission/Maneuver Design and Optimization 5

### Room: Topaz 2, Time: 03:30 PM-04:50 PM

Session Chair: Jason Leonard (KinetX)

**03:30 PM** **160: Statistical Analysis of Optimal Stationkeeping Location and Coast Duration using Stretching Directions**

*Karina Rivera* and Marcus Holzinger*

Continued interest in cislunar space missions has resulted in the development of several orbit maintenance strategies. Many of these techniques focus on Lagrange point orbits (LPO) and aim to reduce fuel consumption. Two of the design parameters that influence the cost of stationkeeping maneuvers in cislunar space are the maneuver location and coast duration. This paper intends to investigate the relationship between maneuver location and coast duration subject to navigation and control uncertainties through the development of sensitivity maps. Understanding whether these sensitive regions mutate or remain unmodified under different sources of uncertainty will serve as a foundation to design more reliable stationkeeping operations.

**03:50 PM** **184: Multiple Space Debris Removal: Optimal Trajectory Design Using Random Key Encoding Scheme**

*Jin Haeng Choi* and Chandeok Park*

This study proposes a single integrated framework for designing trajectories for multiple Active space Debris Removal (ADR) missions. The proposed approach employs the hidden-gene method and the random-key encoding scheme. Both of these technical tools have been successfully used in the field of deep-space trajectory designs but have NOT been used for designing ADR missions to the best of our survey. They are incorporated into an integrated framework to optimally select target debris among candidate pools and determine their removal sequences, as well as to optimize transfer trajectories in a single framework.

**04:10 PM** **131: Perturbed Lambert Problem using the Theory of Functional Connections**

*Daniele Mortari, Franco Criscola* and David Canales Garcia*

A numerical approach to accurately solve the perturbed, multi-revolution, Lambert problem is presented. The approach takes advantage of the Theory of Functional Connection (TFC). TFC allows deriving a functional (constrained expression), which analytically satisfies the boundary value Lambert problem. Comparisons with a high-fidelity orbit integrator are provided in terms of accuracy and execution time.

**04:30 PM** **132: Trajectory optimization using the Theory of Functional Connections**

*Daniele Mortari**

This study numerically solves the two-point boundary value problem of finding the optimal trajectory (in terms of control cost), connecting an initial to a final point on a domain with obstacles and subject to constant gravity. Obstacles are described by potential fields made of oriented 3-dimensional sigmoid ellipsoids. The approach takes advantage of the Theory of Functional Connections (TFC), allowing us to derive functionals (constrained expressions), which analytically satisfy the boundary value problem.

## Thursday, January 19

## Session: Attitude Dynamics, Determination and Control 2

**Room: Topaz 1, Time: 08:00 AM-10:00 AM**

Session Chair: Davide Guzzetti (Auburn University)

**08:00 AM**

**293: Constrained Attitude Control for Small Satellites with a Settling-Time Requirement**

*Micah Schuman, John Martinez*, Hyeongjun Park and Dae Young Lee*

Distributed space telescopes using multiple small satellites have been recently developed to observe sun's flare or X-ray sources. The virtual space telescope missions in Low Earth Orbit (LEO) have short orbit times, and encorporate relative navigation techniques that induce a time constraint to conduct an observation and slew the satellite. Reduced settling time of slew maneuvering becomes critical to achieve precise pointing accuracy through alocation of more time for alignment in relative position and velocity. In this paper, nonlinear model predictive control with pointing constraint considerations is considered to address this unique problem.

**08:20 AM**

**251: Algebraic and Simultaneous Estimation of Attitude Motion and Inertia Properties for Innovative Space Debris Removal**

*Junichiro Kawaguchi* and Tetsuya Kusumoto*

The most important property for the debris removal is the angular momentum vector. The estimation requires that of the inertia property at the same time.
The common way is applying a nonlinear filter, which handles the variated states along the reference trajectories and the parameters.
This paper presents a new direct estimation of both the attitude motion and the inertia properties, excluding the a priori information. Mathematically speaking, the estimation of the inertia tensor results in solving the corresponding Lyapunov matrix equation.
This paper presents, through the numerical simulation, a new scheme for the innovative strategies, contactless & muti-debris removal.

**08:40 AM**

**331: A Multi-Fidelity Assessment of Unsteady Coaxial Rotor Performance on Titan: Dragonfly Entry, Flight and Maneuvering**

*Wayne Farrell* and Michael Kinzel*

In the development of unmanned aerial vehicles (UAV)s for extraterrestrial exploration such as NASA's Dragonfly vehicle accurate modeling of these coaxial rotor loads affects many areas of development such as battery sizing, flight dynamics, control system design and ultimately mission capabilities. In this research we present a multi-fidelity approach to estimate unsteady coaxial rotor performance on the NASA Dragonfly UAV for flight simulation and control. The novelty in this work is the use of multi-fidelity methods to estimate complex coaxial rotor loads suitable for fast model execution.

**09:00 AM** **335: Guidance Templates for Spacecraft Attitude Motion Planning**

*Andrew Miller* and Maruthi R. Akella*

This paper presents a systematic method to stabilize a spacecraft in a finite amount of time, without full knowledge of the inertia matrix, and with arbitrarily small amount of torque. A proportional derivative controller slows down the spacecraft until a finite time controller finishes the stabilization. Both controllers do not require the full inertia matrix and are guaranteed to remain within the torque bound. The guaranteed amount of time to do stabilization is known a-priori in terms of the control gains and upper and lower estimates of principal inertias. The stabilization is demonstrated in simulation of a 3U CubeSat.

**09:20 AM** **362: Center Of Gravity Estimation For Powered Flight Attitude Control**

*Christopher Busic*, Wyatt Johnson and Maruthi R. Akella*

Two center of gravity (CG) offset estimators are proposed to address the need for precise CG characterization during attitude control performed by a powered flight vehicle. The first approach provides a linear time-invariant solution derived from a proportional-derivative controller with feed-forward terms (PD+ structure), where stability is shown through classical linear control arguments. The second design extends the PD+ controller structure with the estimator being derived through a novel Lyapunov function. Both controllers are tested in a high-fidelity simulation environment for performance analysis and comparison.

## Session: Cislunar Space Missions and Operations 2

**Room: Topaz 2, Time: 08:00 AM-10:00 AM**

Session Chair: Carmine Giordano (Politecnico di Milano)

**08:00 AM** **350: Normal Form Methods to Characterize Trajectories in the Circular Restricted Three-Body Problem**

*David Schwab*, Roshan Thomas Eapen and Puneet Singla*

Space Domain Awareness (SDA) architectures must adapt to address the emerging need to survey cislunar space and address associated challenges. One particular challenge is that the chaotic nature of the system makes it difficult to characterize trajectories of resident space objects. Birkhoff normalization transforms the system's Hamiltonian to an integrable form in action-angle variables. Insights from the normal forms may be used to characterize and propagate trajectories near the equilibria points of the circular restricted three-body problem.

**08:20 AM** **299: Independent Verification and Validation of Flight Dynamics Operations for the Korea Pathfinder Lunar Orbiter**

*Craig Nickel, Tiffany Finley, Stephen West*, Jun Bang, Jonghee Bae, SeungBum Hong and Young-Joo Song*

The Korea Aerospace Research Institute (KARI) Korea Pathfinder Lunar Orbiter (KPLO), Korea's first lunar mission, launched on a SpaceX Falcon 9 launch vehicle on August 4, 2022 at 23:08:48 UTC onto a Ballistic Lunar Transfer / Weak Stability Boundary (BLT/WSB) 4-month transfer trajectory to the Moon. A series of Trajectory Correction Maneuvers (TCMs) and Lunar Orbit Insertion (LOI) maneuvers were performed to insert KPLO into its lunar mission science orbit. KARI brought on Space Exploration Engineering (SEE) to perform Independent Verification & Validation (IV&V) of their Flight Dynamics Operations, including pre-launch trajectory analyses, orbit determination, and maneuver planning and reconstruction.

**08:40 AM** **332: Utilization and Validation of DSS-17 on the CAPSTONE Lunar Mission**

*Michael Thompson* and Mitchell Rosen*

The Cislunar Autonomous Positioning System Technology Operations and Navigation Experiment is an ongoing mission to serve as a pathfinder for cislunar operations and navigation for the Lunar Gateway and the greater Artemis program. As part of nominal operations, one of the tracking dishes that CAPSTONE utilizes is DSS-17 at Morehead State University. Through a series of necessary corrections, CAPSTONE has been able to generate radiometric measurements on the same order of noise magnitude as typical DSN measurements. This paper will provide an overview of the necessary processes and early performance of DSS-17 in CAPSTONE orbit determination.

**09:00 AM** **190: Perturbations and Recovery in the Gateway Near Rectilinear Halo Orbit**

*Diane Davis* and Emily Zimovan-Spreen*

The Gateway and CAPSTONE spacecraft are planned to orbit the Moon in a Near Rectilinear Halo Orbit (NRHO) that experiences a 9:2 resonance with the lunar synodic period. Disturbances applied to spacecraft in this NRHO must be corrected to achieve a reasonable lifetime in orbit. This investigation explores the variations between a spacecraft operating under nominal orbit maintenance and the baseline NRHO. The effects of perturbations on an unmaintained spacecraft are explored, with a focus on the time to depart the NRHO. Finally, the costs of correcting disturbances of varying magnitudes are computed using a simple but robust orbit maintenance algorithm.

**09:20 AM** **376: Overview of Blue Ghost Lunar Lander Mission One**

*Scott Yantek*, Adam Licavoli, Daniel Guerrant and William Coogan*

NASA's Commercial Lunar Payload Services program has motivated the creation of a new generation of lunar landers designed to transport and operate commercial and government payloads. One such lander, Firefly's Blue Ghost, will precisely land a suite of NASA and commercial payloads in the Mare Crisium region in the second half of 2024. It will operate the payloads through a full lunar day and into the lunar night. This paper discusses the Blue Ghost lander and its first mission with a focus on Guidance, Navigation, and Control.

09:40 AM **386: Bayesian Angles-only Cislunar Space Object Tracking**

*Keith LeGrand* and Aneesh Khilnani*

Angles-only orbit determination involves the estimation of a satellite's unknown orbit without access to range or velocity measurements. Angles measurements, which are typically passive, are the primary means for tracking distant orbits, where active sensing is energy-prohibitive. This paper presents a Bayesian approach for tracking objects in the cislunar regime using noisy angles measurements. The proposed filter addresses challenges in the cislunar setting, which include dynamics-induced rapid uncertainty growth and long periods of non-observation. The filter is shown to be effective over a range of $L_2$ halo orbit determination problems and to significantly outperform a central-moment based filter.

# Session: Rendezvous, Relative Motion, Proximity Missions, and Formation Flying 3

## Room: Topaz 3, Time: 08:00 AM-10:00 AM

Session Chair: Jeffrey Stuart (Jet Propulsion Laboratory)

08:00 AM **139: Distributed Least Absolute Deviations Estimation**

*Kaushik Prabhu*, Kyle T. Alfriend, Amir Rahmani and Fred Hadaegh*

Distributed algorithms are essential for reducing communication cost, computational complexity, and memory requirement while performing collaborative estimation using multi-agent systems. Additionally, robust estimators are important to prevent the degradation of the estimate in case some of the measurements contain gross errors. Least Absolute Deviations (LAD) estimators have been known to be robust to measurement outliers. To this end, we develop the Distributed Least Absolute Deviations (D-LAD) estimator whereby the agents iteratively exchange information with their immediate neighbors via single-hop communications to gain a network-wide consensus on the estimates. Numerical simulations demonstrating the effectiveness of the D-LAD estimator in the presence of measurement outliers are provided.

08:20 AM **281: Numerical and experimental validation of LIDAR-based Template Matching algorithms for non-cooperative spacecraft pose initialization**

*Alessia Nocerino*, Stefano Piatti, Fabio Saggiomo, Michele Grassi, Giancarmine Fasano, Roberto Opromolla and Christoph Schmitt*

This paper addresses the problem of LIDAR-based pose initialization of a non-cooperative space target, i.e., the estimation of relative attitude and position parameters without any prior information, for close-proximity operations. Specifically, it proposes improvements to state-of-the-art 3D Template Matching techniques. Their effectiveness has been demonstrated through a comprehensive test campaign relying on both synthetic and experimental data, showing improved robustness against unfavorable observation conditions in the pose parameter space. The experimental tests have been conducted in a laboratory facility imaging with the RSV-3000 3D LiDAR by Jena Optronik GmbH different satellite mock-ups.

**08:40 AM** **353: Estimation and autonomous control for multi agent inspection and rendezvous**

*Austin Probe*, MAtthew Ruschmann, John McGreevy, Tabitha King and Ravishankar Mathur*

There is substantially increased demand for space systems with the capability for inspection and rendezvous and proximity operations (RPO) driven by the future markets of satellite servicing, space logistics, and in space assembly and manufacturing (ISAM). This paper details the implementation of flight software for the navigation and control of multiple vehicles performing a cooperative formation flight mission for inspection and rendezvous along with the supporting simulation environment and system testing. Relative estimation is performed based on range measurements derived from visual fiducials and validated with real-time simulation of imagery processed by a software in the loop simulation framework.

**09:00 AM** **393: Onboard Phase Center Calibration of GNSS Antenna Using Relative Position Sensor in Formation Flying**

*Shingo Nishimoto*, Satoshi Ikari and Ryu Funase*

Carrier phase differential GPS (CDGPS) is one of the precise relative navigation technologies. Phase center offset (PCO) and phase center variations (PCVs) are systematic error sources, and the phase center calibration accuracy affects the relative position accuracy of precise formation flying using CDGPS. In-flight phase center estimation has been studied to reduce the ground calibration cost and improve accuracy, but existing in-flight calibration methods use a large amount of GNSS observation data and require frequent ground station use, and increase operating costs. This paper proposes an online calibration method using the relative position sensor data as reference information.

**09:20 AM** **345: Robust Model Predictive Control for Space Cargo Carrying with Uncertain Loads**

*Hyeongjun Park*, Jennifer Hudson and Marcello Romano*

Advancements in space systems enable a variety of on-orbit servicing and assembly missions. As more space systems will be utilized for sophisticated on-orbit servicing missions, the importance of robust and efficient autonomous close-proximity maneuvering capability with uncertain loads grows when a spacecraft carries cargo such as other spacecraft and parts of a huge space architecture. In this paper, a robust model predictive control (RMPC) approach is applied to deal with spacecraft maneuvering problems for cargo carrying with uncertain loads in space. The tube-based RMPC approach is implemended for test cases on an air-bearing testbed. Its performance improvement is analyzed and demonstrated compared with a standard MPC approach.

## Session: Space Situational Awareness, Conjunction Analysis, and Collision Avoidance 2

**Room: Garnet Screening Rm, Time: 08:00 AM-10:00 AM**

Session Chair: Isabelle Jean (Canadian Space Agency)

**08:00 AM** **235: Stochastic analysis of thrust uncertainties in the CR3BP**

*Sharad Sharan*, Amit Jain, Roshan Thomas Eapen, Puneet Singla and Robert Melton*

This paper employs an alternate dynamical model of the Circular Restricted Three Body Problem (CR3BP) to quantify uncertainties associated with spacecraft thrusting maneuvers. The model adopted in this work forges an explicit dependence of the equations of motion on the Jacobi constant, thereby maintaining it constant despite the effect of numerical errors. The conjugate unscented transform technique is used to propagate the system dynamics and state probability densities through the highly nonlinear CR3BP system with reduced computational complexity.

**08:20 AM** **329: Feasibility study of a magnetic system for proximity awareness in formation flying applications**

*Lorenzo Voltini*, Andrea Fuligno, Edoardo Foiadelli, Saba Mohammadi Yengeje, Michela Ferri, Dario Scimone, Niccolò Bruno, Giuseppe De Luca, Luca Aufiero, Ernest Yakubayev, Gabriele Palumbo, Beatrice Olivieri, Dennis Terry Trevino and Lorcan Kelleher*

This feasibility study presents an in-orbit system capable of performing proximity awareness operations. A main spacecraft (Mothership) orbits in formation with smaller satellites (Sentinels), which have the task to produce a low-frequency artificial magnetic field: the Mothership can relate the anomalies in the magnetic fields with the presence of extraneous objects.
The system is designed to be implemented in the architecture of any satellite, working as an auxiliary subsystem. The present system could increase the ability to safely operate the increasing number of spacecraft in space and to perform complex proximity operations.

**08:40 AM** **336: Covariance Based Track Association with Modified Equinoctial Elements**

*Woosang Park* and Kyle T. Alfriend*

This paper analyzes the performance of the covariance based track association (CBTA) with osculating modified equinoctial (OME) and mean modified equinoctial (MME) elements. The OME and MME elements are chosen to reduce the dynamic nonlinearities and to avoid singularity issues on zero eccentricity and zero inclination. The track association performance will be evaluated with percentages of false-positive and false-negative identifications. In addition, the track association success rates will be compared to those of osculating and mean equinoctial elements. The purpose of this paper is to investigate how the dynamic nonlinearity of the modified equinoctial elements affects the performance of the CBTA compared to the case using equinoctial elements.

**09:00 AM** **337: Application of LSTMs to the light curve inversion problem**

*Cesar Enriquez* and Davide Amato*

There is a growing interest in characterizing the attitude dynamics of resident space objects for purposes ranging from active debris removal missions to conjunction assessment. We describe the ongoing research on the obtention of attitude information about an object of known shape, materials, and orbit from its lightcurve using Long-Short Term Memory neural networks. The preliminary results obtained with data generated using a lightcurve simulator developed by Deimos Space show that the attitude of a three-axis stabilized satellite can be predicted with errors in the Euler angles of less than 1 deg in the simplest configurations. It is intended to extend the analysis to more complex cases.

## Session: Attitude Dynamics, Determination and Control 2

### Room: Topaz 1, Time: 10:20 AM-12:00 PM

Session Chair: Davide Guzzetti (Auburn University)

**10:20 AM** **382: EXTRA VEHICULAR OPERATIONS AND PAYLOAD TRANSPORTATION IN MICROGRAVITY WITH A COOPERATIVE FREE-FLYER ROBOT**

*HARUN KHAN*, Ameya Godbole and Kamesh Subbarao*

People are becoming more interested in free-flying robots as they explore deep space. Free-flying robots that can operate independently will be required to perform logistics operations, particularly for the planned Deep Space Gateway. This paper demonstrates how a ‘Coordinated Arm Control’ can be used to move a payload in a microgravity environment to perform some distinct tasks. These tasks include coordinated arm control to move payload in space, capturing an object, and moving a payload where one arm is holding a rigid structure and the other arm moves the payload while maintaining robot’s orientation using a quaternion feedback regulator.

**10:40 AM** **413: 3-axis attitude control method of spacecraft using reflectivity control device**

*Hiroyuki Kobayashi**

We focus on attitude control in deep space, such as SEL2.
solar radiation pressure is a very small force, it is the dominant disturbance in deep space. Therefore, the solar radiation pressure can be changed by using a reflectivity control device (RCD) and used for attitude control of a spacecraft.
In this study, we consider the RCD mounting position and angle, and investigate the placement requirements necessary to realize 3-axis attitude control, torque distribution laws for each device, the driving method for each device, and the sizing method for each device are described.

**11:00 AM** **395: Star Streak Detection for Attitude Estimation in Dynamic Conditions**

*Laila Kazemi* and John Enright*

Agile spacecraft maneuvers typically involve large angular velocities, smearing the star images on the instrument detector. Common star tracker attitude estimation techniques use single star measurements halfway through the exposure. The accuracy and availability of these algorithms drop significantly when star streaks extend beyond the field of view. This paper investigates star streak detection and extracting measurements along the imaged streaks. We developed an analytical model for the streak shape and its errors. We then extend the analysis to estimate a smoothed attitude using multiple measurements from star streaks. We show increased accuracy and availability for star tracker performance in dynamic conditions.

## Session: Cislunar Space Missions and Operations 2

**Room: Topaz 2, Time: 10:20 AM-12:00 PM**

Session Chair: Carmine Giordano (Politecnico di Milano)

**10:20 AM** **425: LOW THRUST TRAJECTORY OPTIMIZATION FOR TRANSPORTING GATEWAY'S POWER AND PROPULSION ELEMENT TO A NEAR-RECTILINEAR HALO ORBIT**

*Alex Pascarella* and Robyn Woollands*

The Power and Propulsion Element is a solar electric propulsion spacecraft and a key module of the Gateway space station,
which is slated to launch in late 2024 and be placed in a Near-rectilinear Halo orbit (NRHO). The focus of this paper is the design and optimization of end-to-end transfer trajectories departing from geosynchronous transfer orbit (GTO)
and arriving at the NRHO via nonlinear programming and indirect trajectory optimization methods.

**10:40 AM** **187: Analysis and Optimization of Robust Trajectories in Cislunar Environment with Application to the LUMIO CubeSat**

*Carmine Giordano* and Francesco Topputo*

Nowadays, the space exploration is going in the direction of exploiting small platforms. However, miniaturized spacecraft pose different challenges both from the technological and mission analysis point of view. While the former is in constant evolution due to the manufacturers, the latter is an open point, since it is still based on a traditional approach, not able to cope with the new platforms' peculiarities. In this work, a revised preliminary mission analysis approach, merging the nominal trajectory optimization with the navigation assessment, is formulated. Then it is specialized for the transfer trajectory of the LUMIO CubeSat trajectory, showing the advantage of this methodology.

**11:00 AM**

### 364: Optimized Trajectory Correction Burns Placement for NRHO Orbit Maintenance

*David Woffinden* and Brayden Barton*

NASA's future Artemis missions plan to utilize a near rectilinear halo orbit (NRHO) in the lunar vicinity to facilitate access to the lunar surface and place other critical assets to support human exploration. This exploration architecture requires a vehicle to remain in the NRHO for long duration periods. Techniques associated with robust trajectory optimization are used to identify the optimized number and placement of trajectory correction burns that accounts for the mission schedule, both a primary and backup navigation system, targeting strategies and burn plan configurations, vehicle venting, thruster selection, and integrated GN\&C performance.

## Session: Rendezvous, Relative Motion, Proximity Missions, and Formation Flying 3

**Room: Topaz 3, Time: 10:20 AM-12:00 PM**

Session Chair: Jeffrey Stuart (Jet Propulsion Laboratory)

**10:20 AM**

### 218: Relative dynamics analysis and trajectory optimization techniques for asteroid rendezvous missions

*Sara Galzignato* and Francesco Leonardi*

This work provides a comparison of some possible dynamics models, trajectory optimization approaches and solution algorithms for a spacecraft asteroid rendezvous. After an initial modelling of the relative dynamics with associated perturbations, three different techniques (grid search, single and multiple shooting) have been employed in order to model stable asteroid periodic orbits. Using a direct method, solved with a metaheuristic solution, hybridized with non-linear programming, a multiple-impulse technique has been implemented for a minimum fuel rendezvous optimization. Finally, a low-thrust optimization, via homotopic indirect approach, has been performed in order to identify the optimal energy and fuel solutions.

**10:40 AM**

### 369: Vision-Based 3D Reconstruction for Navigation and Characterization of Unknown, Space-Borne Targets

*Kaitlin Dennison* and Simone D'Amico*

Multi-agent stereovision and structure from motion are low-resource alternatives to LiDAR and stereophotoclinometry for 3D shape recovery of an arbitrary target. There are gaps in the space-rendezvous literature regarding 3D reconstruction performance with respect to spacecraft swarm geometry, state uncertainty, and clock synchonization. This paper conducts a comprehensive assessment of stereovision and structure from motion performance with respect to many ciritical mission design parameters, including those missing in literature. Recommendations for rendezvous and proximity mission design are extrapolated from the simulation results and then demonstrated for 3D point cloud recovery of an asteroid and a spacecraft.

**11:00 AM** **401: High-Fidelity, Closed-Loop Simulation of Spacecraft Vision-Based Relative Navigation in ROS2**

*Kai Matsuka*, Soon-Jo Chung, Christine Ohenzuwa, Isabelle Ragheb and Leo Zhang*

We present a set of integrated autonomy algorithms along with high-fidelity simulation tools, implemented in ROS2, for rendezvous and proximity operation applications. The autonomy algorithm includes CNN-based object detection, relative navigation, and pointing and formation control pipeline. The ROS2 simulation engine leverages Basilisk, an open-source astrodynamics software, as well as a custom rapid image rending tool based on Neural Radiance Fields (NeRF) that we developed for simulating relative navigation cameras online. Autonomy algorithms and simulation tools are fully integrated and validated in a closed-loop simulation.

**11:20 AM** **398: Precision Landing Comparison between Smartphone Video Guidance Sensor and IRLock by Hardware-in-the-Loop emulation**

*Joao Leonardo Silva Cotta*, John Rakoczy and Hector Gutierrez*

The Smartphone Video Guidance Sensor (SVGS) is an emerging technology developed by NASA Marshall Space Flight Center that uses a vision-based approach to accurately estimate the six-state position and orientation vectors of an illuminated target of known dimensions concerning a coordinate frame fixed to the camera. SVGS is a software-based sensor that can be deployed using resources (CPU and camera) of a host platform and be used for proximity operations and formation flight of drones/spacecraft. This paper aims to compare the SVGS performance in autonomous landing with infrared beacon technology and LiDAR combination.

## Session: Space Situational Awareness, Conjunction Analysis, and Collision Avoidance 2

**Room: Garnet Screening Rm, Time: 10:20 AM-12:00 PM**

Session Chair: Isabelle Jean (Canadian Space Agency)

**10:40 AM** **361: Leveraging Hamiltonian Structure for Accurate Uncertainty Propagation**

*Amit Jain*, Puneet Singla and Roshan Thomas Eapen*

In this work, we leverage the Hamiltonian kind structure for accurate uncertainty propagation through a nonlinear dynamical system. The developed approach utilizes the fact that the stationary probability density function is purely a function of the Hamiltonian of the system. This fact is exploited to define the basis functions to approximate the solution of the Fokker-Planck-Kolmogorov equation. This approach helps in curtailing the growth of basis functions with the state dimension. Furthermore, sparse approximation tools have been utilized to automatically select appropriate basis functions from an over-complete dictionary. A nonlinear oscillator and two-body problem are considered to show the efficacy of the proposed approach.

**11:00 AM** **373: Hybrid Nonlinear Semi-Analytical Uncertainty Propagation for Long-Term Encounter Analysis**

*Yashica Khatri* and Daniel Scheeres*

This work develops a long-term conjunction toolkit by combining an efficient and accurate semi-analytical uncertainty propagation method, realistic dynamics, and a long-term encounter model. The epoch Gaussian uncertainty distribution is split into smaller Gaussian Mixture Model components, that are propagated individually using State Transition Tensors for fast and accurate uncertainty propagation. This method utilizes perturbations due to J2, gravitational attraction due to moon, and SRP through averaged dynamics using a Simplified Dynamical System combined with short-period variation addition at the end. The accurately propagated states and uncertainties are combined with a long-term conjunction model to compute the probability of collision.

**11:20 AM** **417: 3D Reconstruction of Non-Cooperative Resident Space Object using Instant NeRF and D-NeRF**

*Trupti Mahendrakar, Ryan White, Todd Steffen, Basilio Caruso* and Van Minh Nguyen*

The proliferation of non-cooperative resident space objects (RSOs) in orbit has spurred the demand for active space debris removal, on-orbit servicing (OOS), classification, and functionality identification of these RSOs. Recent advances in computer vision have enabled high-definition 3D modeling of objects based on a set of 2D images captured from different viewing angles. This work adapts variations of the neural radiance field (NeRF) algorithm to the problem of mapping RSOs in orbit for the purposes of functionality identification and assisting with OOS. Algorithms are evaluated for 3D reconstruction quality and hardware requirements using datasets consisting of images of a spacecraft mock-up from the ORION facility at Florida Tech.