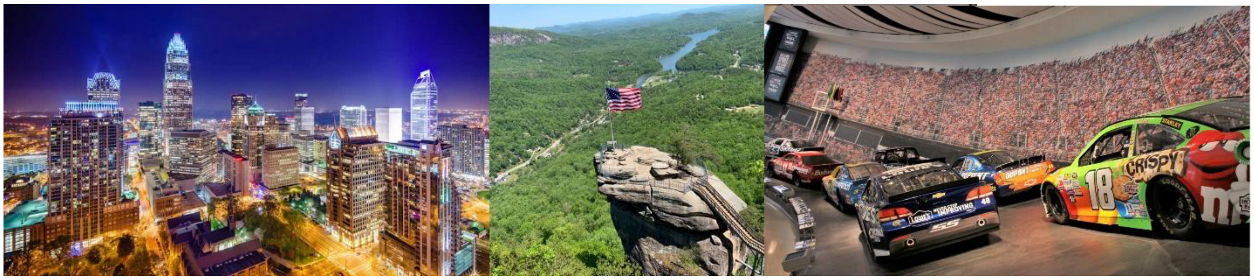

2022 AAS/AIAA Astrodynamics Specialist Conference, Charlotte, North Carolina, August 7-11 2022

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Conference Information

General Information

The 2022 AAS/AIAA Astrodynamics Specialist Conference, hosted by the American Astronautical Society (AAS) and cohosted by American Institute of Aeronautics and Astronautics (AIAA) will be held August 7-11, Charlotte, North Carolina. The conference is co-sponsored by Blue Origin and Infinite Orbits and organized by the AAS Space Flight Mechanics Committee and the AIAA Astrodynamics Technical Committee.

Registration

Registration can be accessed at
https://www.xcdsystem.com/aas/attendee/index.cfm?ID=4zN28b9

Registration Type	Early (On or before Jul 4, 2022)	Regular (After Jul 4, 2022)	Walkups
Full Registration - Current Member (AAS or AIAA)	$750	$870	$970
Full Registration - Non-member, includes one-year AAS membership	$850	$970	$1070
Student Registration - Current Member (AAS or AIAA)	$360	$460	$560
Student Registration - Non-member, includes one-year AAS membership	$405	$505	$605
Retiree Registration - Current Member (AAS or AIAA)	$360	$460	$560
Retiree Registration - Non-member, includes one-year AAS membership	$405	$505	$605

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

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

Conference Proceedings

We are delighted to 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 as follows:

1x extra Proceedings for download	$140
2x extra Proceedings for download	$280

Coronavirus (COVID-19) Considerations

The conference organizers have decided to hold the 2022 AAS/AIAA Astrodynamics Specialist Conference in person at the Sheraton Le Meridien Charlotte Hotel in Charlotte, NC.

We are really looking forward to see a regathering of the professional community and a renewal of our personal connections after more than two years of pandemic.

We will be constantly monitoring all risk indicators and we will be ready to revert to an online event if dictated by health advisories and regulations.

Please monitor the conference website for updates on the conference guidelines. We will abide to any applicable local, state, and federal laws.

The conference guidelines and precautions are as follows:

- According to the latest data from CDC, community infection level for COVID-19 in Mecklenburg County, North Carolina, is **High**.
- In line with CDC, the conference organizers **Strongly Recommend** to:
  - Stay up to date with COVID-19 vaccines
  - Wear a mask indoors in public and on public transportation
  - Wash and sanitize your hands frequently
  - Stay in your hotel room and get tested if you have symptoms
  - Additional precautions are needed if you are at high risk for severe illness
- Detailed information on community levels and COVID-19 prevention are available here: https://www.cdc.gov/coronavirus/2019-ncov/science/community-levels.html#anchor_82254
- **Disposable masks and personal hand sanitizers are provided at registration**

Sponsors

BLUE ORIGIN

Blue Origin was founded with a vision of millions of people living and working in space for the benefit of Earth. Blue Origin is working today to create that future by developing reusable launch vehicles and in-space systems that are safe, low cost, and serve the needs of all civil, commercial, and defense customers. Blue Origin has staff nationwide, offices in nine different locations, and four business units: Rocket Engines, Suborbital Launch (New Shepard), Orbital Launch (New Glenn), and Advanced Development Programs.

The company's Advanced Development Program (ADP) organization is accountable for all of Blue Origin's in-space programs across six broad areas - Lunar Permanence, Space Mobility, Space Destinations, Next-Gen Space Transportation, Advanced Technology, and Honeybee Robotics (subsidiary). ADP is working on multiple internally funded flight programs in each of these program areas. These include our publicly known Blue Moon commercial lunar lander and Orbital Reef. The organization also provides a wide range of concepts, proposals, and technology development projects for ADP's product lines.

The Flight Sciences team in ADP is accountable for delivering capabilities in disciplines related to all aspects of space vehicle flight and flight operation to all of ADP's programs. These capabilities include guidance, navigation and control, navigation sensors, modeling and simulation, aerodynamics, mission design and trajectory optimization, flight autonomy, rendezvous and proximity operations, entry descent and landing, and mission operations. We are hiring exceptional talent at all levels in the disciplines noted above.

Confirm your interest in joining or learning more about Blue Origin and ADP's Flight Sciences Team by clicking here

https://forms.office.com/Pages/ResponsePage.aspx?id=ZsCJ-5NFKEm20lm0YylbnGDpCRAzyfpHvnvu0flKpbBUNTlUNllXWE9YT0lRQ1hNUkZRTTVRWFJaMC4u

INFINITE ORBITS

Infinite Orbits (IO) is a Newspace company founded in 2017 by Telecommunication entrepreneurs and Aerospace Engineers, with a vision to provide reliable, turnkey in-orbit services including life extension to satellite operators globally. With offices in Singapore and Toulouse, France, Infinite Orbits is ready to provide high end NewSpace solutions to cover all satellite servicing needs.

IO's first generation servicer, OrbitGuard, is a small satellite that can autonomously carry out far and near range rendezvous and provides SSA and Inspection services to satellite operators. OrbitGuard is driven by IO's patented state-of-the art ML algorithms and is capable of detecting a target at a distance of several hundred kilometers and to perform pose estimation of an object, with robustness, against extreme lighting conditions. Orbit-Guard 1 & 2 are slated to launch Q4 2022 onwards and provide services from 2023.

Infinite Orbits' Life Extension Servicer, "Endurance", performs autonomous rendezvous & docking and provides full AOCS capability for 5 years to an end of life GEO satellite. Life Extension Services will be available from 2025 onwards.

Conference Location

General Inquiries
https://www.marriott.com/en-us/hotels/cltmd-le-meridien-charlotte/overview/
Le Meridien Charlotte
555 South McDowell Street, North Tower
Charlotte, North Carolina 28204 USA
Phone:+1 704-372-9610
Fax:+1 704-626-3658
Toll-free:+1 888-627-7189

Conference Reservations
To book hotel room at the conference rate please use the following link:
https://www.marriott.com/event-reservations/reservation-link.mi?id=1652201459438&key=GRP&app=resvlink
Online reservation link for AAS 2022

Additional Information
The nightly rooms rates are $129 per night:

- Rates will be at the prevailing government per diem at the time of the conference
- Complimentary Wireless Internet
- Complimentary Meeting Space
- Complimentary Fitness Room Access
- 3 day pre- and post-conference rate availability
- Outdoor Pool

Schedule of Events

	Start	End	Event	Room
Sunday 08/07/2022				
	06:00 PM	09:00 PM	Opening Reception	CJ's Lounge
Monday 08/08/2022				
	08:00 AM	12:00 PM	Relative Motion and Formation Flying I	Carolina D
	08:00 AM	12:00 PM	Dynamical Systems Theory & Trajectory Design	Carolina E
	08:00 AM	12:00 PM	Trajectory, Mission, and Maneuver Design and Optimization I	Carolina A
	08:00 AM	12:00 PM	Space Domain Awareness I	Carolina C
	12:00 PM	01:30 PM	AAS/AIAA Joint Technical Committee Meeting	Cardinal 1 & 2
	01:30 PM	04:50 PM	Guidance and Control of Launch and Atmospheric Entry Vehicles	Carolina D
	01:30 PM	04:50 PM	Attitude Dynamics, Determination and Control I	Carolina E
	01:30 PM	04:50 PM	Trajectory, Mission, and Maneuver Design and Optimization II	Carolina A
	01:30 PM	04:50 PM	Machine Learning and Autonomy in Astrodynamics I	Carolina C
	05:30 PM	07:00 PM	Conference Administration Subcommittee (CAS) Meeting	Cardinal 1
	05:30 PM	07:00 PM	Technical Administration Subcommittee (TAS) Meeting	Cardinal 2
	05:30 PM	07:00 PM	Web Administration Subcommittee (WAS) Meeting	Cardinal 3
Tuesday 08/09/2022				
	08:00 AM	12:00 PM	Orbit Determination and Space Surveillance Tracking I	Carolina D
	08:00 AM	12:00 PM	Machine Learning and Autonomy in Astrodynamics II	Carolina E
	08:00 AM	12:00 PM	Trajectory, Mission, and Maneuver Design and Optimization III	Carolina A
	08:00 AM	12:00 PM	Spacecraft Guidance, Navigation, and Control I	Carolina C

	Start	End	Event	Room
Tuesday 08/09/2022				
	12:00 PM	01:30 PM	AIAA Committee Meeting	Cardinal 1
	01:30 PM	04:50 PM	Relative Motion and Formation Flying II	Carolina D
	01:30 PM	04:50 PM	Machine Learning and Autonomy in Astrodynamics III	Carolina E
	01:30 PM	04:50 PM	Special Session: Juno Mission & James Webb Space Telescope	Carolina A
	01:30 PM	04:50 PM	Asteroid, Earth, and Planetary Missions	Carolina C
	06:00 PM	09:00 PM	Gala Dinner and Awards Ceremony	NASCAR Museum
Wednesday 08/10/2022				
	08:00 AM	12:00 PM	Space Domain Awareness II	Carolina D
	08:00 AM	12:00 PM	Relative Motion and Formation Flying III	Carolina E
	08:00 AM	12:00 PM	Trajectory, Mission, and Maneuver Design and Optimization IV	Carolina A
	08:00 AM	12:00 PM	Orbit Determination and Space Surveillance Tracking II	Carolina C
	12:00 PM	01:30 PM	AAS Committee Meeting	Cardinal 1
	01:30 PM	04:30 PM	Orbital Dynamics, Perturbations, and Stability	Carolina D
	01:30 PM	04:30 PM	Orbit Determination and Space Surveillance Tracking III	Carolina E
	01:30 PM	04:30 PM	Trajectory, Mission, and Maneuver Design and Optimization V	Carolina A
	01:30 PM	04:30 PM	Spacecraft Guidance, Navigation, and Control II	Carolina C
	05:00 PM	06:30 PM	Dirk Brouwer Award Plenary	Mecklenburg
	06:30 PM	09:00 PM	Reception	CJ's Lounge
Thursday 08/11/2022				
	08:00 AM	12:00 PM	Spacecraft Guidance, Navigation, and Control III	Carolina D
	08:00 AM	12:00 PM	Orbital Debris and Space Environment	Carolina E
	08:00 AM	12:00 PM	Trajectory, Mission, and Maneuver Design and Optimization VI	Carolina A
	08:00 AM	12:00 PM	Relative Motion and Formation Flying IV	Carolina C

Each session will have a break of 20 minutes in between. For the morning sessions (Monday to Thursday), the breaks are scheduled from 10:00 AM to 10:20 AM. For the afternoon sessions (Monday to Wednesday), the breaks are scheduled from 3:10 PM to 3:30 PM.

Special Event Information

There will be a catered reception on Sunday (Aug 7) with food and drinks at the Sheraton Le Meridien Charlotte Hotel.

A Gala dinner with awards ceremony will be also held on Tuesday (Aug 9) at the NASCAR Hall of Fame, home of the American auto racing history and heritage (Offsite event).

Jammed-packed with traditional exhibits, the Hall of Fame is fueled with more than 50 interactive experiences like tire-changing stations and realistic racing simulators. The museum has plenty of exhibits with artifacts and NASCAR collections; all designed to get your adrenaline going.

Reception on Sunday as well as tickets to the NASCAR Museum and the associated Gala dinner on Tuesday are included with every registration (Full, Student, and Retiree)

Attendees can purchase additional tickets for each social event during the online registration process as follows:

1x extra Reception ticket (Sunday)	$100
2x extra Reception tickets (Sunday)	$200
1x extra NASCAR Museum and Gala dinner tickets (Tuesday)	$130
2x extra NASCAR Museum and Gala dinner tickets (Tuesday)	$260

The Dirk Brower Award Plenary Lecture will be on Wednesday, August 10 at 5-6.30pm in the Mecklenburg room, followed by a reception with bar.

Tentative Agenda:

5:00-5:05	**Sponsorship activities and mediator**
	Introductions from Simone D'Amico
5:05-5:10	**New award announcement: Emerging Astrodynamicist**
	Presentations from Daniel Scheeres and Terry Alfriend
5:10-6:20	**Dirk Brower Plenary Lecture (1 hour + 10 min Q&A)**
	Introduction from Kamesh Subbarao
	Presentation from Awardee John Crassidis
6:20	**Reception announcement/directions**
	Ossama Abdelkhalik

There will be a Gala Dinner and Award Ceremony on Tuesday 08/09 from 6:00pm to 9:00 pm at the NASCAR museum

Tentative Agenda of Gala Dinner and Award Ceremony:

6:00-6:05	**Sponsorship activities and mediator**
	Introductions from Simone D'Amico
6:05-6:20	**AAS 2021 Space Entrepreneurship Awards and AAS Fellows**
	Introductions from Jim Way, presentation of awardees
6:20-6:30	**John V. Breakwell Student Paper Award**
	Introductions from Robert Melton, presentation of awardees
6:20 (approx)	**Dinner begins**
6:30-6:35	**Best Conference Paper Awards**
	Introduction from Kyle DeMars, presentation of awardee
7:30 (approx)	**End of Gala dinner**
7:30-9:00	**NASCAR Museum**

Additional Technical Information

Presentations

Author presentations (preferably in ppt or pdf format) will be submitted through a web-based system and are due by Thursday August 4th, 2022, 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 Friday July 22nd, 2022, 23:59:59 Eastern Time. A final paper upload is due on or before September 2, 2022 11.59pm US Eastern Time including both pdf format and files in LaTeX or Word format.

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

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

Preprint manuscripts
Physical copies of preprinted manuscripts are no longer available or required for the Space Flight Mechanics Meetings or the Astrodynamics Specialist Conferences. Electronic preprints are available for download at least 72 hours before the conference at

https://www.xcdsystem.com/aas/ for registrants who use the online registration system. Registrants without an internet-capable portable computer, or those desiring traditional paper copies should download and print preprint manuscripts before arriving at the conference.

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

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

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

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

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

Conference Technical Presentation Schedule

Monday, August 08

Session: Relative Motion and Formation Flying I

Room: Carolina D, Time: 08:00 AM-12:00 PM
Session Chair: Jennifer Hudson (Naval Postgraduate School)

08:00 AM

AAS 22-723: HelioSwarm: Swarm Design Methods in Eccentric P/2 Lunar Resonant Orbit

Paul Levinson-Muth, Stephen West and Laura Plice*

Multi-satellite missions provide opportunities for groundbreaking science by enabling simultaneous observations across multiple spatial scales. Lunar resonant orbits provide inexpensive long term access to high Earth orbits but introduce new challenges in spacecraft relative motion. A design process employing gradually increasing analytical fidelity enables flexible swarm design in the cislunar regime. A reference orbit with significant eccentricity evolution presents challenges for multi-satellite swarm design, and a maintenance scheme based on targets developed in a simplified model proves effective at addressing these challenges.

08:20 AM

AAS 22-796: Multibody Dynamics on SE(3)n with Applications to Optical System Formation

Brennan McCann and Morad Nazari*

One method of treating coupled rigid body motion involves framing the problem on the special Euclidean group (SE(3)). This methodology utilizes rotation matrices to represent attitude, which avoids nonuniqueness and kinematic singularity issues. While the formulation of multibody systems on this space has been conducted, it has often considered each spacecraft as a singular element of the group. Furthermore, treatment of these problems on a higher-dimensional manifold have been considered loosely. Here, an exploration of multibody systems on $SE(3)^n$ is conducted and applied to the case study of controlling a spacecraft formation to form an optical observation system.

08:40 AM

AAS 22-826: Feedback Shape Control of Spacecraft Formations in Cislunar Space

Ian Down and Manoranjan Majji*

This paper studies the relative motion dynamics between a chief and deputy spacecraft in cislunar space. Formation shape parameters are defined and transformed into a quaternionic framework using quaternion kinematics and Guass' variational equations. Particular attention is paid to the relative semi-major axis, relative eccentricity, and relative initial mean anomaly, as this subset of planar keplerian orbital elements remain after neglecting the orientation parameters. A Lyapunov control function is developed using methods traditionally applied to attitude control to perform formation shape maintenance and configuration changes. The tracking performance and fuel consumption of this control scheme are analyzed.

09:00 AM

AAS 22-577: 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.

09:20 AM **AAS 22-795: Nonlinear Spacecraft Formation Flying using Constrained Differential Dynamic Programming**

Tomohiro Sasaki, E. Glenn Lightsey and Koki Ho*

This paper contributes to the GNC area by solving nonlinear unconstrained/constrained multi-spacecraft optimal control problems using an existing technique of dynamic programming, differential dynamic programming (DDP). This method is extensively getting attention in Robotics and Aerospace and is extended to a constrained problem in a recent decade. The constrained DDP (CDDP) has proven its optimality and displayed satisfactory numerical performance. This paper utilizes this algorithm and simulated spacecraft formation flying by the Julia Language. Benefiting from the fast computing language, successful CDDP spacecraft formation flying simulation results are shown in this paper without using any numerical optimization solvers.

09:40 AM **AAS 22-646: Modeling and Analysis of Spacecraft Formation Flying Under the Effects of J2, Drag and Lift Perturbation Forces**

*Ayansola Ogundele**

Satellite formation flying, a concept based on the benefits of simpler designs and higher redundancy that smaller spacecraft offer over a single and large spacecraft, is gaining high attention. As a result, there is an immediate need for spacecraft orbit designers to design high-fidelity satellite formation flying dynamics in which the deviation of a satellite from its predetermined path will be minimal. In this paper, via the Euler-Lagrange approach, spacecraft formation flying under the effects of J2, drag, and lift external disturbances is developed. For the inclusion of aerodynamic forces of drag and lift, a rotating Earth is employed.

10:20 AM **AAS 22-815: Relative Coverage Analysis for Hurricane Monitoring Formations**

Pardhasai Chadalavada and Atri Dutta*

In this paper, we consider the problem of determining minimum ΔV for formation initialization subject to constraint on relative coverage repeating after a given period of time. To this end, we develop analytical relationships to determine the relative coverage of CubeSat formations and its connection to the formation’s coverage map. We demonstrate our methodology with numerical simulations, and provide a comparison of error introduced due to assumptions that facilitate the analytical formulation for coverage. The study is particularly useful for deploying formation flying precipitation radars that can take simultaneous measurements to provide a better understanding of internal structure of hurricanes.

10:40 AM **AAS 22-822: Improving the Relative Navigation Solution for Precision Formation Flying Above the GPS Constellation**

Kyle Rankin, Hyeongjun Park, John Krizmanic and Steven Stochaj*

Precision formation flying in orbits above the GPS constellation creates significant constraints for navigation systems due to the limited GPS signal available at these high altitudes. Missions such as NASA's Magnetospheric Multiscale (MMS) have demonstrated that navigation in this environment is possible. This paper This paper seeks to develop navigation filters which solve the relative navigation problem in this environment with a minimal number of constraints placed on attitude control requirements, and trajectory design.

11:00 AM **AAS 22-529: Spacecraft Formation Flying Control Switching Surface Based on Relative Orbital Elements**

*Tyson Smith, John Akagi and Greg Droge**

Switching surface constraints based on the D'Amico ROEs is presented in this paper. ROEs give an intuitive understanding of how the relative motion of a cluster of satellites changes with time. Using a switching constraint based on the ROEs also allows for the control algorithm to take advantage of the natural dynamic motion of the system. This work models each vehicle using an MPC approach, based on the Hill-Clohessey-Whiltshire equations, to plan maneuvers which are simulated using a high-fidelity motion model. An ROE convex polytope is added to the MPC as the switching surface.

11:20 AM **AAS 22-507: Relative Motion Models for the Elliptical Restricted Three Body Problem**

David Zuehlke, Alex Sizemore, Troy Henderson and Andrew Langford*

Relative motion models for objects under the effects of the elliptical restricted three-body problem (ER3BP) are investigated and applied to a chief and deputy satellite scenario in Lunar orbit. Equations of motion for the non-linear relative motion of a chief and deputy satellite are derived and linearized. Analytical solutions for the linearized equations of motion are developed via a matrix exponential solution and MATLAB simulations are used to compare the non-linear, linearized equations, and matrix exponential solutions. The results of this study are applicable to spacecraft relative operations and space domain awareness in cislunar space.

Session: Dynamical Systems Theory & Trajectory Design

Room: Carolina E, Time: 08:00 AM-12:00 PM

Session Chair: Jeffrey Stuart (Jet Propulsion Laboratory)

08:00 AM **AAS 22-738: Cislunar Orbital Transfer Employing Low-Thrust Dynamical Structures**

Rolfe Power and Kathleen C. Howell*

As a greater number of low-thrust missions expect to operate in the cislunar vicinity, an expanded capability for flow-informed low-thrust transfer design is desired. However, inclusion of low-thrust forcing terms in the Circular Restricted Three Body Problem (CRTBP) yields a non-autonomous system lacking the same symmetry properties leveraged for many design applications. The current investigation employs a constant acceleration low-thrust forcing term such that the augmented system retains symmetry and a first integral. This model is applied to the orbit transfer problem leveraging dynamical systems techniques to increase the number of available pathways between orbits in the cislunar region.

08:20 AM **AAS 22-705: Towards A Generalizable Simulation Framework To Study Collisions Between Spacecraft And Debris**

Simone Asci and Angadh Nanjangud*

We present a new approach to modelling and simulation of collision-inclusive multibody dynamics by leveraging symbolic models generated by a computer algebra system (CAS). Similar investigations into contact dynamics on other domains exploit pre-existing black box models of common multibody systems (e.g., industrial robot arms, humanoids, and wheeled robots). In contrast, our focus is on allowing researchers to develop models of novel designs of systems that are not as common or yet to be fabricated: e.g., small spacecraft manipulators. In this paper, we demonstrate the usefulness of our approach to investigate spacecraft-debris collision dynamics.

08:40 AM **AAS 22-616: Tidal Attributes of Low-energy transfers in the Earth-Moon-Sun System**

Stephen Scheuerle and Kathleen C. Howell*

Low-energy transfers leverage multi-body dynamical structures to produce propellant efficient paths. Such trajectories often require a longer flight duration to achieve reduced propellant costs. One type of low-energy transfer in the Earth-Moon-Sun system is termed a ballistic lunar transfer (BLT). The goal of a BLT is to traverse from the Earth to the lunar vicinity by maintaining a reduced insertion maneuver cost. Families of BLTs to conic and multi-body orbits are constructed by leveraging structures within the bicircular restricted four-body problem (BCR4BP). Transfer solutions in the BCR4BP are employed as initial guesses when exploring paths in the higher-fidelity ephemeris model.

09:00 AM **AAS 22-758: Hindsight is 20/20: A Retrospective on Applying Interactive Visualization Techniques to Mission Design & Nagivation**

Jeffrey Stuart, Emine Basak Alper Ramaswamy and Jonathan Richmond*

Many challenges within Mission Design and Navigation benefit from the application of interactive visualizations to aid human operators. Chief benefits include intuitive presentation of complex information, a reduced cycle time between question and answer, and lowering barriers to communication, especially with non-experts. In this work, we provide a retrospective look at the implementation of several visualization prototypes tailored to selected MDNav analysis tasks. We also discuss lessons learned in adapting visual design and analysis approaches to the field of astrodynamics.

09:20 AM **AAS 22-766: Full N-Body Problem in the Geometric Mechanics Framework and its Reduction to Circular Restricted Three-Body Problem**

Morad Nazari, David Canales Garcia, Brennan McCann, Eric Butcher and Kathleen C. Howell*

A compact formalism for rigid body motion dynamics is presented in a general reference frame based on geometric mechanics. This formalism, proposed on the special Euclidean space of the Lie group, naturally accounts for the orbit/attitude coupling due to the gravitational moments and forces for the full N-body problem. Furthermore, the expressions for energy are provided. The special case for the circular restricted full three-body problem (CRF3BP) is then considered, with equations provided in the spacecraft's body and barycentric rotating frames. Several trajectories are computed for the CRF3BP, and are compared with the traditional CR3BP model.

09:40 AM **AAS 22-756: Orbital Elements for the Restricted Three-Body Problem**

Luke Peterson and Daniel Scheeres*

The Keplerian orbital elements are a set of parameters that uniquely describe a two-body trajectory. Once perturbations are imposed on two-body dynamics, one often studies the time evolution of the orbital elements. Moving to the Restricted 3-Body Problem (R3BP), the Keplerian orbital elements are no longer well-defined. In this work, we define a set of Birkhoff orbital elements which are defined locally about any bounded special solution in the R3BP. Birkhoff orbital elements are defined using action-angle coordinates in a Birkhoff normal form. We include detailed examples around the five equilibria, L1−5, in the Earth-Moon R3BP.

10:20 AM **AAS 22-748: Trajectory Design in the Hill Zonal Problem**

Nicola Baresi and Lamberto Dell'Elce*

Upcoming missions towards remote planetary moons will fly towards chaotic dynamical environments that are significantly perturbed by the oblateness of the host planet. This paper introduces a new time-periodic set of equations of motion that is based on Jezwinski's analytical solution of the zonal equatorial problem. Such a system, hereby referred to as the Hill zonal problem, remains populated by families of two-dimensional quasi-periodic invariant tori that are hereby calculated by means of homotopy continuation procedures. The obtained quasi-periodic trajectories are finally investigated for the mission analysis and design of future planetary moons explorers.

10:40 AM **AAS 22-548: Three-dimensional Lagrangian Coherent Structures in astrodynamics systems using Differential Algebra**

Jack Tyler and Alexander Wittig*

Lagrangian Coherent Structures (LCS) have received attention for profiling dynamical behaviour and identifying separatrices between dynamical features in systems with arbitrary time-dependence. However, the method's use in astrodynamics has thus far largely been limited to two-dimensional motion. This talk will present DA-LCS, a new numerical method that uses Differential Algebra to find LCS in three-dimensional astrodynamics systems automatically and to higher accuracy than standard approaches. We demonstrate the method's out-performance of standard approaches on the Sun-Mars Elliptic-Restricted Three-Body Problem, and go on to show how the orbit parameterisation used affects the LCS found.

11:00 AM **AAS 22-688: Mitigating the impact of Momentum Unloads on Station Keeping around Libration Point orbits**

Ariadna Farres, David Folta, Adam Michaels and Cassandra Webster*

Station-keeping maneuvers are required to maintain a spacecraft close to a Libration point orbit, where the size of these maneuvers depends on different perturbations and any unmodeled forces. In many missions, despite being small, frequent momentum unloads can have a large impact on the size station-keeping maneuvers. In this paper we will show that applying momentum unloads in the Linear Approximation to the Minimum Escape (LAME) direction can significantly reduce their impact on the station-keeping delta-v budget.

11:20 AM **AAS 22-605: Implementation of the Solar Exclusion Zone Burn Through Maneuvers for DSCOVR to Preserve Fuel for the Gyro-less Spacecraft in a Sun-Earth L1 Lissajous Orbit**

Jeremy Petersen, John Lorah, Joseph Park, Jason Long and Edward Malinowski*

DSCOVR (Deep Space Climate Observatory) is a National Oceanic and Atmospheric Administration (NOAA) space weather, space climate, and Earth observation satellite operating in a Sun-Earth L1 Lissajous orbit. This investigation will summarize the two-burn maneuver campaign performed in Summer 2021 to transfer DSCOVR from the collapsing phase into the expansion phase of the Lissajous orbit to avoid the Solar Exclusion Zone (SEZ). The two-maneuver campaign performed in July and August 2021 was successful and will result in saving the mission 31 kg of fuel reserved for SEZ maneuvers which are no longer required until 2026 or 2027.

Session: Trajectory, Mission, and Maneuver Design and Optimization I

Room: Carolina A, Time: 08:00 AM-12:00 PM
Session Chair: Diane Davis (a.i. solutions, Inc.)

08:00 AM

AAS 22-506: Earth to Moon L2 NRHO Transfers using a Cycler Approach in the Restricted Three Body Problem

Mario Innocenti, Tommaso Donatini, Fabio D'Onofrio and Giordana Bucchioni*

The return to the Moon is programmed for the near future according to the current ARTEMIS roadmap. Using a cycler orbit, periodically intercepting an Earth LLO and the Moon target NRHO, may provide several mission advantages. Two different types of transfers between cycler orbits and the Gateway's NRHO are considered. The first consists of Lambert arcs numerically adjusted in the CR3BP. The second utilizes stable and unstable manifolds of an intermediate L1 Halo orbit. Comparison is performed in terms of ΔV s and times of flight, in order to analyze the advantages of one technique with respect to the other.

08:20 AM

AAS 22-545: Orbit Maintenance Burn Details for Spacecraft in a Near Rectilinear Halo Orbit

Diane Davis, Frederick Miguel and Emily Zimovan-Spreen*

The baseline orbit for Gateway is a Near Rectilinear Halo Orbit (NRHO) in a 9:2 resonance with the lunar synodic period. A spacecraft in this slightly unstable NRHO requires orbit maintenance (OM) for long-duration operations. An updated OM algorithm is described, including burn magnitudes and directions, desirable OM burn locations along the NRHO, and the effects of changing weighting parameters and tolerances. Costs associated with visiting vehicles arriving and departing are considered, including the effects of delayed OM burns. The effects of constraints on OM attitudes are investigated, as are cost deltas associated with differences in the selected baseline NRHO.

08:40 AM

AAS 22-564: GNC Performance Analysis and Robust Trajectory Optimization for NRHO Rendezvous Mission Design

David Woffinden, Simon Shuster, David Geller and Stefan Bieniawski*

This paper presents a robust trajectory optimization technique and applies it to a cislunar mission profile, beginning with TLI and ending with NRHO rendezvous. First, the performance of candidate NRHO rendezvous strategies are evaluated using linear covariance analysis, and a baseline trajectory and navigation suite is established. Next, the robust trajectory optimization approach is presented. It assumes an existing reference trajectory and optimizes the locations of midcourse correction maneuvers and utilization of navigation sensors to minimize dispersions in Delta-V or final position. Results show that optimal solutions achieve lower dispersion with fewer navigation sensors as compared to the baseline.

09:00 AM

AAS 22-624: Optimal Control in the Circular Restricted Three-Body Problem Using Integration Constants

Walter Manuel and Simone D'Amico*

This paper presents a method for spacecraft to transfer between halo orbits at the optimal delta-v cost. Halo orbits are three-dimensional periodic orbits that form in the Circular Restricted Three-Body Problem (CR3BP). CR3BP motion can be decomposed, expanded to extract more linear terms, and then parameterized to use integration constants (IC) as state variables. By incorporating reachable set theory, the IC can be used to achieve optimal control via an impulsive solver. This helps fill current gaps in the state-of-the-art by approaching optimal control in a way that is potentially better suited for new and emerging spacecraft trajectory design requirements.

09:20 AM

AAS 22-636: Analysis of the escape strategies from the 1:1 resonance capture based on low-thrust propulsion
*Wail Boumchita**
The 1:1 resonance between the period of revolution of a spacecraft and the period of rotation of an asteroid causes strong perturbations in the motion of the spacecraft. Therefore, it is important to analyze this phenomenon and how to counteract its effects efficiently to ensure robustness to the space mission. Taking the Dawn mission as a case study, this study concentrates on systematically analyzing how to escape from resonance by considering changes in thrust magnitude and direction. A representation in phase space helps to understand how and when to perform the necessary maneuvers to escape from the resonance capture.

09:40 AM

AAS 22-612: Accessing the Vicinity of the L1 Libration Point via Low-Energy Transfers Leveraging Quasi-Periodic Orbits
Brian McCarthy and Kathleen C. Howell*
Quasi-periodic orbits offer a wide range of destinations in cislunar space. In this investigation, a design framework is developed to construct low-energy transfers to the L1 vicinity leveraging quasi-periodic motion. A strategy is offered to build such transfers in both the Circular Restricted Three-Body Problem (CR3BP) and the Bicircular Restricted Four-Body Problem (BCR4BP). First, families of heteroclinic connections between quasi-periodic tori in the L2 region and L1 region are constructed. Second, quasi-periodic motion from the BCR4BP is leveraged to design families of transfers from Earth to the L1 vicinity. Finally, solutions are transitioned to a higher-fidelity ephemeris model.

10:20 AM

AAS 22-641: Coplanar Circular-to-Circular Orbit Transfer Guidance with Constant Thrust
Siddarth Kaki and Maruthi R. Akella*
A semi-analytical solution for circular-to-circular planar orbit transfers is presented. In particular, the problem is addressed with a judiciously chosen maneuver sequence consisting of radial thrust, velocity normal thrust, and coast arcs. The radial thrust segments admit fully-analytical solutions, while the velocity normal thrust portion only admits a semi-analytical solution. For a given constant-acceleration thrust value, the range of radii to which the orbit can be changed is presented with two different schemes. Orbit escape is also demonstrated with successive applications of the first scheme. However, all the presented solutions are suboptimal in terms of time and fuel-use.

10:40 AM

AAS 22-838: Acceleration-Based Switching Surfaces for Impulsive Trajectory Design in Restricted Three-Body Dynamics
Keziban Saloglu and Ehsan Taheri*
This study introduces a tool that solves impulsive trajectory optimization for circular restricted three-body dynamics.
The tool includes the cost gradients to satisfy first-order necessary conditions expressed by Primer Vector Theory. The low-thrust solution is obtained by solving the problem using the indirect method. High-acceleration solution is found by sweeping through the acceleration value. The impulsive part is formulated via direct methods, as a nonlinear programming problem, to minimize the total delta-v. Gradients of the cost are in terms of primer vector to locate optimal solution when the cost function is minimized.

11:00 AM **AAS 22-647: Robust Nonlinear Optimal Control Using Koopman Operator Theory**

Erica Jenson, Mai Bando, Kyousuke Sato and Daniel Scheeres*

This paper utilizes Koopman operator (KO) theory to generate robust optimal control laws for nonlinear systems with control-dependent noise. The evolution of a nonlinear system can be described using linear equations via KO theory such that linear control algorithms can be applied to a KO system without the need for linearization about a nominal trajectory. This paper uses data-driven methods to approximate KO systems. A robust linear control law is then applied to a KO system, effectively generating a nonlinear controller. This technique will be demonstrated for robust nonlinear control in the Hill three-body problem.

11:20 AM **AAS 22-660: Robust Trajectory Optimization for Guided Powered Descent and Landing**

Grace Calkins, David Woffinden and Zachary Putnam*

A robust trajectory optimization approach for guidance algorithm gain selection for powered descent and landing is developed. This approach uses a genetic algorithm to determine optimal guidance algorithm parameters while accounting for uncertainty and sensor fidelity with linear covariance analysis. The optimal gains are found for the braking phase of a lunar landing mission. Scenarios with differing sensor suites and qualities are considered, with objective functions to minimize variability in propellant usage or terminal position. Results show that optimal gains may result in 20% performance improvements over the baseline in propellant usage and terminal accuracy.

Session: Space Domain Awareness I

Room: Carolina C, Time: 08:00 AM-12:00 PM

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

08:00 AM

AAS 22-736: System Design and Analysis For Cislunar Space Domain Awareness through Distributed Sensors

Gregory Badura, Yuri Shimane, Koki Ho, Alaric Gregoire, Brian Gunter, Christopher Valenta, Mariel Borowitz, John Christian and Alicia Sudol*

This paper summarizes an ongoing Georgia Tech effort to provide a cislunar space domain awareness (SDA) solution based on distributed space-based sensors that complement existing Earth-based assets. Distributed space-based SDA architectures complement one another via a diverse constellation geometry to overcome the sensing limitations of any single architecture. Our unique technical approach to this solution focuses on analyzing the links to a "Cislunar Custody Chain" via a diverse team of sensor, policy, and orbital dynamics experts. Our analysis will provide solutions towards creating the best actionable policy knowledge given the challenges of tracking and detecting objects within the Cislunar volume.

08:20 AM

AAS 22-540: Tracking Spawning Events in Cislunar Space Using a Label-Partitioned GLMB Filter

Benjamin Reifler and Brandon Jones*

The cislunar environment presents unique challenges for space situational awareness due to its chaotic dynamics. These dynamics pose a particular challenge when dealing with spawning events, such as explosions, collisions, and cubesat deployments, because they make it difficult to predict the motion of spawned objects and determine their origins. This paper covers work to apply a label space partitioning technique to the generalized labeled multi-Bernoulli (GLMB) filter with spawning and assess its ability to handle spawning events in cislunar space.

08:40 AM

AAS 22-640: Preliminary Comparative Assessment of L2 and L3 Surveillance Using Select Cislunar Periodic Orbits

Jacob Dahlke, Adam Wilmer and Robert Bettinger*

Space Domain Awareness (SDA) in the cislunar environment is an area of growing demand due to the increased interest in the region. However, there is limited analysis on the efficacy of satellites in the cislunar domain to perform surveillance and also to be tracked. The present study investigates both target satellites and surveillance satellites in periodic orbits throughout the cislunar domain to evaluate the efficacy of SDA in this region. Specific assessments include target satellites in periodic orbits around L2 and L3 and sensor satellites in periodic orbits around L4, L5, and "touring orbits" that covers the entire cislunar region.

09:00 AM

AAS 22-648: Resident Space Objects Detection and Tracking Based On Artificial Intelligence

Marco Mastrofini, Gilberto Goracci, Ivan Agostinelli, MOHAMED SALIM FARISSI and Fabio Curti*

Resident Space Objects detection and tracking are challenging problems in the framework of the Space Situational Awareness due to the dramatic increasing of space debris around the Earth. In this work, an AI-based approach for Image Processing, Objects Detection and Tracking oriented to space optical sensors applications is investigated. The Image Processing and Object Detection tasks are demanded to Convolutional Neural Networks while the tracking of objects inside the sensor's FOV is formulated as an optimization problem. Dataset creation for the network training, algorithm design process and results with real images will be shown along with traditional performance indices.

09:20 AM

AAS 22-722: Multiple Hypothesis Tracker with Sensor Tasking feedback for Space Object Detection and Tracking

*Naga Venkat Adurthi and Thibault Richard**

In this paper, we develop approaches to make the multiple hypothesis tracker more efficient in detecting and tracking large number of space object with limited sensors. Multiple hypothesis tracker is one the conventional approaches to track multiple targets when there is an ambiguity in measurement-to-target associations. This is often the case when tracking multiple target with cameras that measure the azimuth and elevation angles, where it is challenging to assign the measurements to the multiple targets observed in multiple frames. Gating is a standard procedure to prune unnecessary branches of the multiple hypothesis tracker tree but may not be sufficient

09:40 AM

AAS 22-730: Satellite Maneuver Detection by using Covariance based Track Association

Woosang Park and Kyle T. Alfriend*

This paper introduces a spacecraft maneuver detection algorithm based on Covariance-based track association. A maneuver time and delta-v are estimated by finding the minimum Mahalanobis distance between two orbits. Two approaches are introduced. First, under the two-body motion assumption, a semi-analytic solution is available by finding two optimality conditions to make derivatives of the Mahalanobis distance with respect to the maneuver time and delta-v equal to zeros. Second, a fully numerical solution is introduced for the case considering J2 perturbation. The numerical simulation result shows it performs better than the minimum-distance method. This maneuver detection algorithm will improve the performance of uncorrelated track

10:20 AM

AAS 22-797: Applications of Artificial Intelligence Methods for Satellite Maneuver Detection and Maneuver Time Estimation

Nicholas Perovich, Zachary Folcik and Rafael Jaimes*

We show that machine learning (ML) and neural network (NN) classifiers improve the detection rate and false alarm rate of maneuver detection systems. Current statistical methods achieve a detection rate of 94% and false alarm rate of 8%. When trained on simulated maneuver and non-maneuver data, ML achieves a detection rate and false alarm rate of 91% and 1%, respectively. NN achieves 97% and 0.3%. We also propose using NNs as methods for timestamping maneuvers. Current threshold methods are accurate to within 24-48 hours. Results from this study are forthcoming and will be included in the final paper.

10:40 AM

AAS 22-695: Space, The Finite Frontier: Rapidly Computing the Reachability of Electric Propulsion Spacecraft

Prashant Patel and Daniel Scheeres*

Estimating the reachability of electric propulsion spacecraft is important for space domain awareness, robust mission design, constellation management, space traffic management, and many other applications. We develop a fast, automated (no user initial guess), and scalable algorithm for estimating the reachable set. We achieve this by carefully constructing the problem to avoid a two-point boundary value problem. We apply the algorithm to several cases including those with strong multi-body effects and measure its performance. This demonstrates the robustness and speed of our method to estimating the reachable set for electric propulsion spacecraft.

11:00 AM **AAS 22-674: How Many Satellites Can We Fit in Low Earth Orbit?: Capacity integrating Risk-based and Intrinsic Methods**

Miles Lifson, Andrea D'Ambrosio, David Arnas and Richard Linares*

Growth in the active Low Earth Orbit (LEO) satellite population will result in conjunctions feature two active satellites making up a larger portion of overall conjunction risk. Greater and more concentrated orbital density also increases the severity of collisions at densely populated altitudes. Prior LEO slotting work describes ways to coordinate orbital traffic into mutually safe sets of slots and shells. This paper demonstrates a method to modify a previous particle-in-a-box source-sink evolutionary model to include the effects of orbital slotting and estimates the resulting risk reduction and corresponding increases to orbital capacity from slotting.

11:20 AM **AAS 22-658: Analysis of the LEO orbital capacity via probabilistic evolutionary model**

Andrea D'Ambrosio, Simone Servadio, Peng Mun Siew, Daniel Jang, Miles Lifson and Richard Linares*

This paper focuses on the analysis of the evolution of the LEO population and the estimation of LEO orbital capacity using a new multi-shell multi-species source-sink model, where the species considered are active and derelict satellites, and debris (trackable and non-trackable). Moreover, collisions and atmospheric drag effects are taken into account, including the influence of solar activity. Indeed, the Jacchia-Bowman 2008 (JB2008) thermospheric density model is adopted within the proposed framework. Finally, the long-term predictions of LEO population and the measurement of its orbital capacity are provided analyzing different scenarios to study the sensitivity of that evolution to different variables.

11:40 AM **AAS 22-531: Adaptive Estimation for Continuous Thrust Maneuver Detection and Tracking**

Amit Bala, Jonathan Kadan, Cameron Harris, Kevin Schroeder and Jonathan Black*

With increasing interest in Space domain awareness and the characterization of the growing resident space object(RSO) population, the process of detecting and tracking of RSO maneuvers has become of increased interest. This work proposes a comparative study to evaluate techniques of maneuver detection and tracking from the continuous thrust maneuver perspective. Several multiple model adaptive estimation techniques will be evaluated through use cases tracking an RSO through a detected continuous thrust maneuver event. From the outset of the proposed research, a comparitive analysis on the performance of the adaptive estimators will be provided, leading towards improved space domain awarness capabilities.

Session: Guidance and Control of Launch and Atmospheric Entry Vehicles

Room: Carolina D, Time: 01:30 PM-04:50 PM
Session Chair: Kamesh Subbarao (University of Texas at Arlington)

01:30 PM

AAS 22-604: Nominal and Emergency Rocket Landing Guidance using Quadratic Programming

Hubert Ménou, Eric Bourgeois and Nicolas Petit*

This paper presents nominal and emergency Powered Descent Guidance methods for rocket landing, in the presence of atmosphere. Nominal guidance is seen as a minimum-effort correction problem to a reference trajectory, in free final-time, with non-trivial aerodynamic effects and mixed state-control constraints. It is solved using Quadratic Programming. Emergency guidance – dealing with infeasible nominal scenarios – is described as a hierarchical negotiation of landing problem parameters and is solved using Linear Programming. Nominal and emergency guidance are merged into a single unifying algorithm. The overall computational complexity remains low and compatible with on-board usage. Numerical simulations are provided.

01:50 PM

AAS 22-717: Convex Approach to Stochastic Control for Autonomous Rocket Pinpoint Landing

Boris Benedikter, Alessandro Zavoli, Zhenbo Wang, Simone Pizzurro and Enrico Cavallini*

This paper presents a convex approach to the stochastic optimal control of landing rockets that explicitly accounts for mass uncertainty. By including a probabilistic description of the uncertainties in the dynamics, the algorithm provides a closed-loop control policy that drives the system from an initial probability distribution to the desired final one, compensating for the uncertainties associated with the return of a launch vehicle stage after separation. Thanks to several convexification methods, the stochastic optimal control problem is solved with low computational complexity. Extensive Monte Carlo campaigns prove the robustness of the attained policies and estimate the achievable landing accuracy.

02:10 PM

AAS 22-764: Estimation of aerodynamic angles and wind components for a launch vehicle

Vincenzo D'Antuono, Giovanni Di Monaco, Alessandro Zavoli, Guido De Matteis, Simone Pizzurro and Enrico Cavallini*

This paper proposes a technique based on filtering for the estimation of aerodynamic angles and wind components for a launch vehicle (LV) in atmospheric flight. The virtual sensor for estimating aerodynamic angles is based on an extended Kalman filter which exploits measurements of LV inertial accelerations and angular rate measured by an IMU, inertial velocity provided by GPS and airspeed velocity by the air data system. Preliminary results were obtained for a case study involving the atmospheric flight of the first stage of Ares-I, demonstrating that reasonably accurate estimations can be achieved by proper tuning of process and noise covariance.

02:30 PM

AAS 22-821: Ambiguity Remediation in Space Launch Vehicles with Parameter Uncertainties: A Comparison between Special Euclidean Group and Dual Quaternions

Matthew Wittal, Julio Cesar Benavides, Brennan McCann and Morad Nazari*

Legacy methods for launch vehicle estimation and control are performed primarily using quaternions and dual quaternions, which outperform Euler angles since quaternions have no singularities yet exhibit the disadvantage of unwinding. Launch vehicle dynamics and control also contain noisy attitude measurements yet precise position and velocity measurements. In this work, a launch problem is simulated using formulation on special Euclidean group SE(3) and dual quaternions. Noisy measurements are interpreted using an unscented Kalman filter in both SE(3) and dual quaternions frameworks. In both cases, model reference control methodologies are applied and compared with each other in terms of the computational

02:50 PM **AAS 22-848: Attitude Stabilization of Swirl Injection Hybrid Launch Vehicle**

Ryan Kinzie and Dongeun Seo*

An affine parameter-dependent Lyapunov function based controller and adaptive controller are proposed to stabilize a launch vehicle with an internally originating torque. The motivation for this research arises from the new development of rocket engines that swirl combustion gases to gain combustion stability benefits, and in the case of hybrid rocket engines, fuel regression benefits as well. This research adds to a novel investigation into control techniques for stabilizing a launch vehicle with an internal torque and concludes with the recommendation of the use of an adaptive controller for launch vehicles similar to the one developed here.

03:30 PM **AAS 22-690: A Mars Entry Robust Optimal Guidance Strategy under the Presence of Modelling Errors and Disturbances**

Emily Palmer and Anil Rao*

The optimal trajectory design and guidance of a Mars entry problem is considered under the presence of modelling errors. The altitude at the end of entry is maximized. An optimal guidance strategy is developed that accounts for possible modelling errors and perturbations. The method developed performs mid-course corrections at constant intervals, at which the quantities being constrained are evaluated and the optimal control problem is re-solved. If the constrained quantities are within a user chosen range of the limit, the objective is changed to minimize the maximum value of the constrained quantity when re-solving the problem.

03:50 PM **AAS 22-783: Reachable Set Computation and Analysis for Hypersonic Atmospheric Re-Entry Vehicles**

Jinaykumar Patel, Prabhjeet Arora and Kamesh Subbarao*

This paper focuses on the computation of reachable sets for nonlinear dynamical systems. The hypersonic atmospheric re-entry problem is considered and time evolution of reachable sets is studied for the system subject to implicit controls that are nonlinear in the governing equations of motion. For providing background, the reachable set synthesis process is first examined for linear systems (with and without nonlinear perturbations) and, then nonlinear dynamical systems. The reachable sets are estimated using the COntinuous Reachability Analyzer (CORA) toolbox in MATLAB. Representative simulations for the linear and nonlinear systems are performed and the results discussed to illustrate the

04:10 PM **AAS 22-800: Maneuver Design and Flight Control for a Martian Probe Network**

Samuel Albert and Hanspeter Schaub*

Networks of small probes on the Martian surface are a mission class of current interest. Maneuver design is presented for networks ranging in size from regional to global, such that all probes are delivered by a single carrier spacecraft. The control authority afforded by a subsonically-deployed drag skirt is quantified for varying dynamic pressure constraints and final ballistic coefficients, and the resulting landing site dispersions are estimated through a Monte Carlo analysis based on relevant dispersions.

04:30 PM

AAS 22-803: Feasibility and Performance Analysis of Magnetohydrodynamic Control for Aerocapture at Neptune

Danny Nguyen, Soumyo Dutta, Robert Moses, Brian Gunter and Hisham Ali*

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

Session: Attitude Dynamics, Determination and Control I

Room: Carolina E, Time: 01:30 PM-04:50 PM

Session Chair: Andrew J. Sinclair (Air Force Research Laboratory)

01:30 PM

AAS 22-597: Error-Covariance Reset in the Multiplicative Extended Kalman Filter for Attitude Estimation

*F. Landis Markley, Yang Cheng and John Crassidis**

This paper presents a study of the reset step in the multiplicative extended Kalman filter (MEKF). The reset does not add new information, but it changes the reference frame for the attitude error-covariance. This results in an error-covariance reset that is very different from the measurement update of the error-covariance in the EKF. The effects of using an error-covariance reset in the MEKF are analyzed in this work. The results from this work can be applied to any application involving attitude estimation as part of its process, such as inertial navigation.

01:50 PM

AAS 22-673: An Extended Particle Swarm Optimization Approach for Full Attitude State Estimation from Multiple Sequential Light Intensity Measurements

Stephen Gagnon and John Crassidis*

This paper presents an extension to the multiplicative particle swarm optimization approach to attitude estimation, allowing for the full rotational state to be estimated including the angular velocity. This extension requires sequential light intensity measurements from multiple observers in order to observe angular rate information in addition to attitude information. This optimization routine is applied to the problem of attitude estimation from light intensity measurements and compared to a mutli-start gradient based approach.

02:10 PM

AAS 22-724: Adaptive Observers for Angular Velocity Estimation using Rate-Integrating Gyroscopes

Arjun Ram and Maruthi R. Akella*

Rate-Integrating Gyroscopes do not directly provide angular velocity measurements and hence require an observer for full state feedback. This work focuses on systems whose inertia matrix is unknown and presents an adaptive nonlinear observer which provides asymptotically converging estimates of the angular velocity state as well as an update law for the inertia parameter.

02:30 PM

AAS 22-512: Equivalence and Calibration of Euler Angles with Less Nonlinear Attitude Parameterizations

*Eric Butcher and Andrew J. Sinclair**

Euler angle sets remain a popular attitude parameterization in many aerospace applications such as aircraft dynamics and control despite disadvantages including high nonlinearity indices and singularities no more than 90 degrees from any attitude. The equivalence of the linearized Euler angle error kinematics, related through linearized transformations with less nonlinear attitude parameterizations, is demonstrated assuming either additive or multiplicative error definitions. This equivalence is used to develop calibrated linearized Euler angle solutions that utilize the linearized solutions for parameterizations with lower nonlinearity indices and thus provide greater accuracy.

02:50 PM

AAS 22-755: Onboard Inertia Tensor Estimation Using Constrained Gaussian-Mixture Particle Flow

John Helmuth and Kyle DeMars*

This work proposes a new approach to spacecraft inertia tensor estimation using Gaussian mixture particle flow. Accurate knowledge of a spacecraft inertia tensor enables enhanced attitude control performance, but the inertia tensor is often imprecisely known. Given appropriate actuation and sensor data, these mass properties can be estimated on orbit, but the nonlinear dynamics and constraints on the inertia tensor make this challenging, especially with computing constraints. Gaussian mixture particle flow provides an accurate, flexible estimation approach that can handle nonlinearities and address state constraints without an undue computational burden.

03:30 PM **AAS 22-541: Constrained Attitude Path Planning via Least Squares MRP-based NURBS Curves**

Riccardo Calaon and Hanspeter Schaub*

This paper deals with the reorientation of a spacecraft that is subject to hard rotational constraints. Inertial keep-out and keep-in directions are considered, which must be respected by the specified body-fixed boresight directions as the spacecraft performs the maneuver. This paper investigates the use of a least squares NURBS curve fit to provide a continuous and twice-differentiable reference trajectory based on a sequence of constraint-compliant attitude waypoints sampled in a 3D MRP workspace. Considerations are made on using a least squares NURBS fit, as opposed to NURBS interpolation, to yield an effort-optimal solution that is less dependent on the level of sample grid refinement.

03:50 PM **AAS 22-806: Pointing and Image Motion Performance Analysis**

*Mark Pittelkau**

Spacecraft pointing performance requirements have traditionally not been tied directly to image motion effects on image quality of optical payloads. The system Optical Transfer Function (OTF), the spatial frequency response, is one indicator of image quality. The system OTF is shaped in part by the image motion OTF, which potentially can impose a limit on image quality. The objectives of this paper are 1) present image motion OTFs and their parameterization, 2) define the parameters in terms of pointing performance, 3) show how to analyze a system to obtain the parameters, and 4) answer "What Is Jitter".

04:10 PM **AAS 22-579: Campaign Results for the Adaptive Control Experiment on DSX**

Andrew J. Sinclair and Larry Davis*

The Adaptive Control Experiment (ACE) was conducted on the Demonstration Science Experiment (DSX) satellite from 2019 to 2021. The experiment utilized DSX's large booms to study methods for system identification and attitude control of flexible space structures. Campaign 1 gathered system-identification data, and helped verify deployment of DSX's booms. Campaign 2 suffered a variety of issues that severely limited the conducted experiments. Campaign 3 implemented feedback controllers designed using the on-orbit identified model. Increase in control bandwidth, relative to the conventional attitude controller used throughout the DSX mission, by a factor up to 93.8 was demonstrated.

04:30 PM **AAS 22-625: Modular Dynamic Modeling of Hinged Solar Panel Deployments**

Galen Bascom and Hanspeter Schaub*

This paper expands prior multi-body dynamics with the back-substitution method to apply to deployable spacecraft panel configurations. Earlier work focused on using hinged panel dynamical models to study first order flexing of solar panels. This study is interested in modeling deployable single- or double-hinged structures which are allowed to flex about a nominal deployment angle. External motor torques are included in the dynamical formulation to create a physics-based deployable panel simulation. The focus is on developing a modular software implementation using the back-substitution method. Here the full nonlinear coupling is retained while providing an implementable software solution.

Session: Trajectory, Mission, and Maneuver Design and Optimization II

Room: Carolina A, Time: 01:30 PM-04:50 PM

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

01:30 PM

AAS 22-559: Optimal Earth-Moon Low-Energy Transfers in Bi-Circular Model Using Differential Evolution

*GARIMA AGGARWAL**

It is common knowledge that a low-energy transfer trajectory is extremely sensitive to initial condition. In this paper, we compute an optimal Earth-Moon low energy transfer in the Four-Body Bi-Circular Model using an effective and fast optimization tool called Differential Evolution. Using prior knowledge on the role of the invariant manifolds in coupled Sun-Earth and Earth-Moon 3-Body systems, we limit the search of the initial condition of the Earth-Moon low entry transfer trajectory to obtain a faster, optimal and accurate solution to the unknown initial condition. The optimization tool is simple to use and the formulation of the problem does

01:50 PM

AAS 22-603: A Motion Primitive Approach to Trajectory Design in a Multi-Body System

Thomas Smith and Natasha Bosanac*

This paper presents a motion primitive approach to trajectory design in multi-body systems. Motion primitives sampled from fundamental solutions, e.g. periodic orbits and stable/unstable manifolds, supply a discrete summary of segments of the phase space. Graphs of motion primitives are constructed and searched to produce primitive sequences that form candidate initial guesses for transfers of distinct geometries. Transfers are then computed from each initial guess using multi-objective constrained optimization. This approach is used to construct transfers in the Earth-Moon circular restricted three-body problem with impulsive maneuvers, demonstrating the potential for a primitive-based approach to support rapid and efficient trajectory design.

02:10 PM

AAS 22-583: Designing Spatial Transfers in Multi-Body Systems using Roadmap Generation

Kristen Bruchko and Natasha Bosanac*

Rapidly constructing trajectories in multi-body systems that adhere to various constraints relies heavily on a human-in-the-loop with sufficient understanding of the solution space. Probabilistic roadmap generation offers an alternative approach to efficiently summarizing the solution space and rapidly constructing constrained trajectories. In this paper, a graph is constructed using roadmap generation in the Earth-Moon circular restricted three-body problem to summarize the solution space near the vicinity of L_1 and L_2. Then, a graph search algorithm is used to repeatedly search the graph to construct a variety of spatial transfers between libration point orbits.

02:30 PM

AAS 22-708: Stochastic Sequential Convex Programming for Robust Low-thrust Trajectory Design under Uncertainty

Kenshiro Oguri and Gregory Lantoine*

This study develops a framework that designs robust low-thrust trajectories under uncertainty. Any space trajectories are subject to state uncertainty due to imperfect state knowledge, random disturbances, and partially known dynamical environments. Such uncertainty and associated risks must be properly quantified and taken into account in the process of trajectory design, ensuring a sufficiently low risk of causing hazardous events.

Combining stochastic optimal control and sequential convex programming, our framework incorporates the stochastic effects of orbit determination and maneuver execution errors and designs both a reference trajectory and flight-path control plans to ensure the constraint satisfaction under uncertainty.

02:50 PM **AAS 22-569: Concurrent Optimization of Gravity-Assist Low-Thrust Trajectory with Power and Propulsion Subsystem Sizing**
Yuri Shimane, Dyllon Preston and Koki Ho*
Low-thrust technology is a key driver in current and upcoming space exploration missions due to their high specific impulse.
A challenge when designing low-thrust trajectories is due to the inherent coupling of the various subsystems with the trajectory, as the spacecraft mass greatly affect the obtainable acceleration by a given propulsion subsystem. To this end, this work proposes an approach for coupling the sizing process of the power and propulsion subsystems to a direct-transcription-based trajectory optimization problem, which enables a concurrent trade-space exploration of both the trajectory and the spacecraft system.

03:30 PM **AAS 22-698: MULTIPLE GRAVITY ASSIST MISSION PLANNING BY RANDOM KEY ENCODING SCHEME**
Jin Haeng Choi and Chandeok Park*
This study presents a novel approach to interplanetary mission planning, which considers continuous, discrete, and variable-size design spaces simultaneously. The proposed approach effectively converts a continuous search space into the discrete solution space by adopting the random-key (RK) encoding scheme and hidden-value mechanism. Three different RK encoding schemes are adopted to effectively convert continuous variables into discrete variables. They are applied to evolutionary algorithms and are tested through two benchmark problems of multiple gravity assist (MGA) mission planning. The overall analysis shows that the proposed approach based on RK encoding scheme is effective in solving MGA mission planning.

03:50 PM **AAS 22-771: Dynamically Leveraged Automated (N) Multibody Trajectory Optimization (DyLAN)**
*Ryne Beeson**
Preliminary trajectory mission design has become a more difficult problem in recent years. In particular for missions in multiple gravitational body environments with low thrust propulsion spacecraft. Non-technical constraints such as low budgets and rapid cadence increases the difficulty of the task. In this paper, we present the automated global optimization software package: Dynamically Leveraged Automated (N) Multibody Trajectory Optimization (DyLAN) developed by CU Aerospace L.L.C. DyLAN brings together dynamical systems techniques with automated global optimization algorithms that have found success with interplanetary design tools. We describe the framework, key research results, and demonstrate the efficacy of the tool on relevant problems.

04:10 PM **AAS 22-741: Leveraging Medium-Fidelity Dynamical Models for Transitions into a Higher-Fidelity Model in the Cislunar Region**
Beom Park and Kathleen C. Howell*
While the Earth-Moon Circular Restricted Three-body Problem (CR3BP) provides useful dynamical structures that are successfully leveraged for actual missions, transitioning the CR3BP periodic orbits into a higher-fidelity ephemeris model remains nontrivial. The transitioning procedure may benefit by more consistently incorporating information from an intermediate, medium-fidelity model. This work examines the Elliptic Restricted Three-Body Problem (ER3BP) and Bi-Circular Restricted Four-Body Problem (BCR4BP) as

medium-fidelity models. The value of these models within the context of a transition to a higher-fidelity ephemeris model is compared, and some sample transitions are demonstrated.

04:30 PM

AAS 22-829: A Novel Method for Comparing Interplanetary Trajectories for Early Mission Design

Daniel Owen and Brian Kaplinger*

Tisserand plots are widely used in early mission design to plan interplanetary trajectories, especially ones with gravity assists. These plots, however, do not include information about transfer time. This paper presents a new method of analysis uses that produces plots which include transfer time as well as departure and arrival excess velocity. This method will allow mission designers to better compare and select trajectories based on all of the relevant design parameters. This paper also presents methods for optimizing these trajectories according to the three design variables, transfer time, departure excess velocity, and arrival excess velocity.

Session: Machine Learning and Autonomy in Astrodynamics I

Room: Carolina C, Time: 01:30 PM-04:50 PM

Session Chair: Davide Guzzetti (Auburn University)

01:30 PM

AAS 22-567: Augmenting Periodic Orbit Discovery with Physics-Informed Neural Networks

John Martin and Hanspeter Schaub*

Periodic orbits are highly desirable in astrodynamics. These orbits guarantee that a spacecraft or satellite will return to the same initial state after some period with no need for corrective burns or station keeping. Unfortunately, identifying such orbits in real systems is challenging, particularly in environments for which the dynamics are highly non-keplerian such as around asteroids and comets. This paper investigates how the new Physics-Informed Neural Network gravity model can be used to rapidly identify periodic motion in these complex environments.

01:50 PM

AAS 22-754: Orbit Determination with Maneuver Estimation in Cislunar Environment Via Physics Informed Neural Networks

Luca Ghilardi, Andrea Scorsoglio and Roberto Furfaro*

In this paper, orbit determination of a body in the Circular Restricted Three-Body Problem (CRTBP) lunar environment, subjected to maneuvers, is solved via Physics-Informed Neural Networks (PINNs). The model uses a single-layer feed-forward neural network called Extreme Learning Machines, which allows good generalization and fast training speed. PINNs are characterized by a loss function made by a least-square estimator and a regularization parameter based on the equations of motion of the problem. The latter term forces the solution to be compliant with the physics of the problem. The model's inputs are angular observations, right-ascension, and declination.

02:10 PM

AAS 22-809: Development of Methodologies for Modeling and Estimation of Drag Parameters Using Physics-Informed Neural Network

Smriti Nandan Paul and Piyush Mehta*

The rampant growth of man-made space objects makes correct estimation of dynamical parameters important for accurate orbit determination. In this paper, we first develop methodologies that use physics-informed neural network (PINN) for estimation of Earth gravitational parameter and J2 coefficient. The PINN penalizes training loss function for predictions violating underlying dynamics. For our preliminary problems, we use normalized/trigonometric functions of Keplerian elements. We use Gauss's Variational Equations to augment traditional loss function. We demonstrate that PINN accurately estimates the parameters of our preliminary problems. The final goal is to expand the PINN methodologies for modeling and estimation of drag parameters.

02:30 PM

AAS 22-645: Optimizing a Long Short-Term Memory Neural Network to Forecast Solar Radio Flux

Charles Fry and Craig McLaughlin*

Solar radio flux at 10.7 cm (F10.7) is a widely used proxy indicator of extreme ultraviolet solar radiation. Increased solar EUV radiation increases density in the thermosphere and therefore atmospheric drag at high altitudes, altering the orbits of satellites and other objects. Thus, to improve orbit determination accuracy and collision avoidance particularly in low Earth orbit (LEO), a forecast of F10.7 is desirable. A novel way of conducting time series forecasting is using artificial recurrent neural networks, specifically long short-term memory (LSTM) networks. This paper presents optimization of an LSTM network's structure to reach minimal error when forecasting F10.7.

02:50 PM **AAS 22-820: Performance Enhancements for Autonomous Flight Control Using Hierarchical Ensembles of Autonomous Decision Systems**

Peter Jorgensen and Robert H. Bishop*

Autonomous flight control is enabled through multi-level competitive-cooperative decision making expert systems based on fuzzy logic. Genetic algorithm tuning is applied to the hierarchical ensembles of autonomous decision systems (HEADS) framework. Training simulation results verify improved performance. Results are shown for simulation under different (non-training) mission conditions demonstrating generalized robust performance. Finally, simulated results are presented for the training and non-training mission scenarios under simulated fault conditions showing robustness of system health and payload operations to unplanned partial failures.

03:30 PM **AAS 22-666: Autonomous Anomaly Detection Via Unsupervised Machine Learning**

Felipe Giraldo Grueso, Renato Zanetti and Michelle Simon*

Autonomous anomaly detection can be divided into two sub-problems: regression and classification. In the regression analysis, a machine learning model is trained to reconstruct a signal, and the classification process categorizes the reconstruction error as anomalous or nominal. This paper studies the autonomous anomaly detection problem and proposes improvements to its sub-problems. For the regression analysis, it was found that including the physics of the signal in the model yields a lower reconstruction error and decreases convergence time compared to a data-driven model. The classification approaches studied showed that Gaussian and cluster-based thresholding techniques with pruning can outperform non-parametric dynamic thresholds.

03:50 PM **AAS 22-671: Autonomous Vision-Based Docking via Meta-Reinforcement Learning**

Andrea Scorsoglio, Luca Ghilardi and Roberto Furfaro*

In this paper, meta-reinforcement learning is used to optimize a policy for autonomous rendezvous and docking using optical measurements. A convolutional-recurrent neural network is used to map observations, simulated using a physically-based 3D rendering engine, directly to the optimal thrust and torque command. The network is trained using proximal policy optimization in a meta-reinforcement learning framework. The objective is to control the chaser to successfully dock with the target while staying within a conical approach corridor and not losing sight of the target.

04:10 PM **AAS 22-720: Autonomous navigation around Didymos using CNN-based Image Processing**

Aurelio Kaluthantrige, Jinglang Feng, Iosto Fodde and Jesús Gil-Fernández*

The Early Characterization Phase (ECP) is a proximity operation of the European Space Agency's HERA mission with the objective of conducting physical and dynamical characterizations of the target binary asteroid system Didymos. This paper develops a pipeline to estimate the state of HERA spacecraft around the target body during the ECP using a Convolutional Neural Networks-based Image Processing algorithm. The algorithm uses the images captured with the on-board camera to estimate the pixel position of the centroid of Didymos and to measure the pseudorange with respect to it, and then combines these two measurements to estimate the relative state of the spacecraft.

04:30 PM **AAS 22-750: Embedded Homotopy for Convex Low-Thrust Trajectory Optimization with Operational Constraints**

Christian Hofmann and Francesco Topputo*

A novel homotopic approach for convex low-thrust trajectory optimization is developed to improve convergence, accuracy, and computational effort compared to state-of-the-art methods. The homotopy is embedded into the optimization process where the homotopic parameter is dynamically adjusted based on the constraint violation. This method is combined with a high-fidelity model where the complexity of the dynamics and constraints is successively increased. In particular, n-body dynamics, solar radiation pressure, and variable specific impulse and maximum thrust are considered. Moreover, operational constraints are included to account for no-thrust periods. The effectiveness is shown in several examples.

Tuesday, August 09

Session: Orbit Determination and Space Surveillance Tracking I

Room: Carolina D, Time: 08:00 AM-12:00 PM
Session Chair: Jason Leonard (KinetX)

08:00 AM

AAS 22-560: A Norm-Minimization Algorithm for Solving the Cold-Start Problem with XNAV
Linyi Hou and Zachary Putnam*
An algorithm is presented for solving the cold-start problem using observations of x-ray pulsars. Using a norm-minimization-based approach, the algorithm extends an existing banded-error intersection model to three-dimensional space while reducing compute time by an order of magnitude. The impacts of relativistic effects, the parallax effect, Shapiro delay, and higher-order pulsar timing models on the solution of the cold-start problem are assessed. The feasibility of solving the cold-start problem via XNAV is revisited with the improved models and prior knowledge requirements are discussed. Monte Carlo simulation techniques are used to establish measurement uncertainty bounds and determine algorithm accuracy.

08:20 AM

AAS 22-561: Initial Orbit Determination from Sequential Line-Of-Sight Velocity Measurements
Linyi Hou and Zachary Putnam*
Existing velocity-based initial orbit determination algorithms require simultaneous observations along multiple lines of sight to obtain the velocity vector of a spacecraft. We introduce a new, generalized technique that allows velocity observations along different lines of sight to occur sequentially, which can reduce the number of sensors required to enable velocity-based initial orbit determination. The accuracy of the new algorithm is compared against existing techniques for a variety of orbits. Orbit estimation errors are analyzed with respect to Keplerian orbit elements via Monte Carlo simulations.

08:40 AM

AAS 22-585: Single-pass, Single-station, Doppler-Only Initial Orbit Determination
Anthony Holincheck and Janet Cathell*
Range-rate can be determined from the Doppler shift of signals transmitted by satellites. To date, no direct solution to the initial orbit determination (IOD) problem for range-rate measurements has been discovered. A recent algorithm reduces the IOD problem for circular orbits to a search on orbit radius when using multi-station, mutli-pass observations for a satellite. We show that a search on radius and inclination provides solutions to the IOD problem with as few as three range-rate observations from a single station on a single pass. This reduces the IOD problem to the theoretical minimum number of observations.

09:00 AM

AAS 22-743: Phase-Independent Spawning Models for Initial Orbit Determination
Benjamin Reifler, Sofia Gianina Catalan and Brandon Jones*
We present a constrained admissible region-based spawning model for multiple hypothesis tracking designed to enable faster track initialization than a spontaneous birth model or classical initial orbit determination methods by accounting for the correlation between the orbit of a newly detected object and the orbit of its parent. The model is shown to significantly reduce the size of the admissible region in both a LEO/radar and a GEO/optical sensor scenario. The LEO example is then used to initialize a single-target tracking simulation, in which the spawned object is tracked successfully.

09:20 AM

AAS 22-687: Geometric Initial Orbit Determination from Bearing Measurements

Timothy Duff, Michela Mancini, Anton Leykin and John Christian*

Initial orbit determination (IOD) from only bearing measurements is a classical problem in astrodynamics. The classical solutions of Gauss, Laplace, and others can solve this problem with three bearing measurements collected at known times. In this work, we apply concepts from algebraic geometry to investigate purely geometric solutions to this same problem. It is shown that five optical sightings at unknown times may be used to determine the orbit of an unknown spacecraft. The solution only requires knowledge that the spacecraft is following a conic orbit, with no need for any orbit propagation as part of the IOD process.

09:40 AM

AAS 22-767: An 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, i.e. scenarios where both the sensor and the object being sensed are orbiting the Earth. Initial Orbit Determination for space-to-ground scenarios has been well studied but much less attention has been paid to the space-to-space problem. A new hybrid approach combining elements of the Gauss and Laplace methods is developed. Traditional space-to-ground techniques and the new hybrid method are evaluated for particularly stressful space-to-space scenarios. Both short and long observation arcs are considered and metrics are applied to compare the performance of the various methods.

10:20 AM

AAS 22-770: Initial Orbit Determination for the CR3BP Using Particle Swarm Optimization

David Zuehlke, Taylor Yow, Daniel Posada, Joseph Nicolich, Christopher Hays, Aryslan Malik and Troy Henderson*

This work utilizes a particle swarm optimizer (PSO) for initial orbit determination for a chief and deputy scenario in the circular restricted three-body problem (CR3BP). The PSO is used to minimize the difference between actual and estimated observations and knowledge of the chief's position with known CR3BP dynamics to determine the deputy initial state. Convergence is achieved through limiting particle starting positions to feasible positions based on the known chief position, and sensor constraints. Parallel and GPU processing methods are used to improve computation time and provide an accurate initial state estimate for a variety of cislunar orbit geometries.

10:40 AM

AAS 22-801: Semi-Analytical Rapid Orbit Determination Approach for Perturbed Two Body Problem

Erin Cope, Puneet Singla and Roshan Thomas Eapen*

Ensuring flight safety by rapidly determining orbits of observed objects is of paramount importance to maintain the economic value of space assets. While optical sensors routinely provide angles-only data, traditional algorithms for orbit determination depend on methods that approximate the nonlinear dynamics of resident space objects. The goal of this paper is to develop tools to incorporate information from the nonlinear dynamics while keeping the implementation of these orbit determination methods computationally tractable. Specifically, this paper proposes to combine advancements in semi-analytic satellite theory with statistical methods to accurately compute state transition matrices in a Jacobian free manner.

11:00 AM

AAS 22-701: On the Theoretical Interpretation of a New Stable Inverse of Discrete Time Systems

*Xiaoqiang Ji and Richard Longman**

When a sensor on board a spacecraft is to repeatedly perform a desired maneuver, the feedback control system will produce a repeated tracking error history based on the control system bandwidth. Instead one can solve the inverse problem to find that command that causes the control system to follow the desired output path. Unfortunately, this inverse problem results in an unstable command input function. There is an existing approach in the literature to bypass this difficulty. The authors have developed an alternative approach. This paper develops an understanding of how these two stable inverse approaches are related.

11:20 AM

AAS 22-517: Revisiting Universal Variables for Robust, Analytical, Nonsingular Orbit Propagation under Vinti's Potential

*Ashley Biria**

To meet the growing complexity and demands of modern spacecraft missions, analytical solutions to initial value problems see continued use, typically supporting global searches of large design spaces. These efforts often employ universal two-body orbit propagators for their recognized speed and robustness, but many applications, like active space debris removal, would benefit from a comparable propagator with greater accuracy. Vinti propagators, which consider planetary oblateness, may serve this purpose, but existing Vinti solutions possess computational difficulties in certain orbital regimes. To mitigate these deficiencies, the present study develops and validates a third-order universal Vinti propagator free of computational difficulties.

11:40 AM

AAS 22-518: Using Vinti's Intermediary to Define an Unperturbed Boundary Value Problem with Planetary Oblateness

*Ashley Biria**

Numerous methods exist for solving the Lambert problem, the two-point boundary value problem (BVP) governed by two-body dynamics. Many applications would benefit from a solution to a perturbed Lambert problem; a few studies have attempted to solve one. Establishing a larger pool of solution methods gives practitioners greater latitude in choosing the solution that best suits their needs. The present goal is to solve a BVP that includes oblateness by way of Vinti's potential, rendering the problem mathematically unperturbed. This BVP is first defined and then converted to a system of equations that is amenable to an iterative solution.

Session: Machine Learning and Autonomy in Astrodynamics II

Room: Carolina E, Time: 08:00 AM-12:00 PM

Session Chair: Donghoon Kim (University of Cincinnati)

08:00 AM **AAS 22-563: Reinforcement Learning for Small Body Science Operations**

Adam Herrmann and Hanspeter Schaub*

On-board planning and scheduling will become a requirement for future missions to small bodies due to the uncertainty in the environment and round-trip light-time delay. Reinforcement learning is well-suited for on-board planning and scheduling because of the observation-action-observation feedback loop. This work formulates a partially observable Markov decision process for a small body science operations problem where the objective is to maximize the weighted sum of targets imaged and downlinked while avoiding resource constraint failures. Monte Carlo tree search and supervised learning are used to compute generalized and near-optimal policies.

08:20 AM **AAS 22-841: Small Body Reconnaissance By Multiple Spacecraft Via Deep Reinforcement Learning**

Kento Tomita, Yuri Shimane and Koki Ho*

Asteroid investigation by spacecraft is one of the most important space exploration missions. Typical asteroid visiting missions use a single spacecraft equipped with various kinds of science instruments, but this makes the entire mission less robust and reduces the flexibility of the science investigation by each sensor. This paper proposes multi-agent spacecraft missions where each spacecraft has different kinds of science instruments. In this study, we apply multiagent deep reinforcement learning (MARL) approach to optimize the orbit and sensor target of each spacecraft. We will evaluate the proposed approach by computer simulation with the existing asteroid model.

08:40 AM **AAS 22-576: Online Remote Sensing Tasking Method with Input Uncertainty Awareness**

Hao Peng and Xiaoli Bai*

This paper presents a study of including the input uncertainty into the Bayesian optimization (BO) based remote sensing tasking method. Besides the measurement noise already considered in the classical Gaussian process (GP) models, the location uncertainty resulting from attitude control or sensor pointing errors are handled. Specifically, we use an expected GP (EGP) model with a kernel that takes two normal distributions as input. Simulation result shows that additional performance improvement can be achieved in certain conditions. We also draw conclusions about in what situation the input uncertainty must be considered and what the expected improvement would be.

09:00 AM **AAS 22-552: Multi-step Look-ahead Intelligent Task Planning for Earth Observing Satellite**

Rabiul Hasan Kabir and Xiaoli Bai*

In this paper, we study an intelligent task planning strategy for an Earth Observing Satellite using multi-step Bayesian Optimization (BO). An earlier study showed significant improvement in observation performance achieved by implementing the BO pointing strategy compared to the simple nadir point approach, which however does not take into consideration the possible future outcomes when deciding the current action. To overcome this limit, we design a modified Continuous Belief Tree Search algorithm which enables the multi-step look-ahead optimization in the continuous action domain. Preliminary results have shown the improved performance of the multi-step BO over the myopic one.

09:20 AM **AAS 22-609: Satellite Constellation Task Planning for Intelligent Remote Sensing: Detach and Joint Mode for Multi-satellite Update**

Hao Peng and Xiaoli Bai*

This paper reports the recent achievements in of Bayesian optimization (BO) based tasking method for intelligent remote sensing using satellite constellations. Previous results have already shown that a two-level Gaussian process (GP) surrogate model can improve the observation performance for a small scale constellation. In this paper, two critical problems for a larger scale constellation are tackled. First, how to handle the situation that multiple satellites are observing the same region of interest, i.e., whether the satellite should work independently or jointly. Second, how the coupling of the global and local surrogate models can further improve the performance.

09:40 AM **AAS 22-652: Game-Theoretic Task Allocation for Multi-Satellite Earth Observation Problems**

Andrew Miller, Yoonjae Lee, Efstathios Bakolas and Maruthi R. Akella*

A task scheduling framework based on game theory is developed for a multi-satellite earth observation problem. These satellites attempt to find a joint task schedule that maximizes the (nonlinear) global objective function associated with the quality of observations affected by repeating observations and maneuver costs. We formulate this task allocation/scheduling problem as a multiplayer non-cooperative game and discuss a decentralized game-theoretic solution approach. By proving the game is a potential game, a pure-strategy Nash equilibrium that corresponds to a local maximizer of the global objective function is guaranteed to exist. Simulation results showcase the performance of our framework.

10:20 AM **AAS 22-765: Applying Monte Carlo Tree Search for Orbit Selection in Multi-Agent Inspection**

John Lathrop, William Cook, James Ragan and Soon-Jo Chung*

We present an improved approach in selecting formations of stable Passive Relative Orbits (PROs) for deputy satellites to aid in the inspection and reconstruction of a target spacecraft in orbit around Earth. We model this selection as a sequential decision-making problem where only the final formation's information value is assessed, as opposed to previous greedy algorithms that added each orbit based on the immediate information gain. We develop a Monte Carlo Tree Search algorithm (MCTS) to efficiently solve this problem and compare its performance versus a greedy algorithm over test PRO spaces of varying complexity.

10:40 AM **AAS 22-638: You Only Crash Once: Improved Object Detection for Real-Time, Sim-to-Real Hazardous Terrain Detection and Classification for Autonomous Planetary Landings**

Timothy Chase, Chris Gnam, John Crassidis and Karthik Dantu*

Vision-based systems have been used with great success to detect hazardous terrain during landing phases on missions such as Mars 2020 through template matching approaches. However, these templates require substantial pre-flight mission cost and effort to produce. The latest in autonomous driving research here on Earth has given way to new methods that can more generally detect hazards in a real-time, safety critical embedded envrionment. To that end, we present *You Only Crash Once*, a YOLO-based hazardous terrrain identification system with domain adaptation elements for use in simulation-to-real planetary landing applications and in-situ operation.

11:00 AM

AAS 22-851: Missing and noisy data recovery for planetary landing by Conditional Generative Adversarial Network

Tatsuwaki Nakagawa, Kento Tomita and Koki Ho*

Hazard detection and avoidance is critical for any mission that involves planetary landing. Recently, many hazard detection algorithm such as Autonomous Landing Hazard Avoidance Technology and Artificial Neural Network has been using LiDAR-based Digital Elevation Map . As LiDAR can be a powerful tool, it can have missing and noisy data which can significantly impact the performance of Hazard Detection algorithm. Conditional adversarial network such as context encoder and Generative Adversarial Imputation Nets has been used to overcome those caviot to eliminate noise and in-paint missing data in high accuracy.

11:20 AM

AAS 22-811: Detection and Initial Assessment of Lunar Landing Sites Using Neural Networks

Daniel Posada, Jarred Jordan, Angelica Radulovic, Lillian Hong, Aryslan Malik and Troy Henderson*

Robotic and human lunar landings are a focus of future NASA missions.
Precision landing capabilities are vital to guarantee the success of the mission, and the safety of the lander and crew.
During the approach to the surface there are multiple challenges associated with Hazard Relative Navigation to ensure safe landings.
This paper will focus on a passive autonomous hazard, detection, and avoidance sub-system to generate an initial assessment of possible landing regions for the guidance system.
The system uses a single camera and the MobileNetV2 architecture to detect and discern between safe landing sites and hazards such as rocks, shadows, and craters.

Session: Trajectory, Mission, and Maneuver Design and Optimization III

Room: Carolina A, Time: 08:00 AM-12:00 PM

Session Chair: Pradipto Ghosh (The Johns Hopkins University-Applied Physics Laboratory)

08:00 AM

AAS 22-544: Global Optimization of The Moon Tour Problem

Ahmed Ellithy, Jacob Englander and Ossama Abdelkhalik*

This paper presents a tool for moon tour trajectory optimization using global optimization techniques. The Moon tour problem is usually designed using graphical methods which extensively depend on assumptions and the designer's intuition. Global optimization techniques automate this design problem without any prior assumptions.

The Evolutionary Mission Trajectory Generator (EMTG) is coupled with the genetic algorithm to optimize the moon tour problem autonomously. The problem is solved for a fixed sequence first, and then the variable sequence is included in the second step. A two-body dynamics model generates an initial guess to the three-body design problem.

08:20 AM

AAS 22-551: Chance-constraint optimization of interplanetary trajectories with a hybrid multiple-shooting approach

Nicola Marmo and Alessandro Zavoli*

Dynamics uncertainties and stochastic disturbances on a nominal open-loop control law may affect a space mission by deviating the probe from the designed optimal trajectory. This manuscript proposes a systematic approach for the design of a closed-loop control law, where quantitative information concerning uncertainty on the system dynamics and stochastic navigation errors are directly accounted for in the optimization process. A hybrid single/multiple-shooting strategy is used to respectively propagate the state mean and probability distribution, resulting in an efficient performance and stability of the numerical method. The method is applied on a test case with encouraging results.

08:40 AM

AAS 22-656: Minimum-Fuel Trajectory Optimization in the Earth-Moon System Using Adaptive Gaussian Quadrature Collocation

George III Haman and Anil Rao*

The problem of minimizing spacecraft fuel consumption during transfers in the Earth-Moon system is considered. The motion of the spacecraft, modeled as a point mass, is governed by the dynamics of the controlled circular restricted three-body problem. The continuous-time, multiple-phase optimal control problem is then discretized using an adaptive Legendre-Gauss-Radau quadrature collocation method and transformed into a sparse nonlinear programming problem to be solved using sequential quadratic programming. This investigation includes transfer trajectories from an initial Earth orbit to L1 to demonstrate that direct collocation provides competitive results as a robust alternative to indirect and direct single- and multiple-shooting techniques widely used.

09:00 AM

AAS 22-704: Upgrading Different Low-Thrust Gravity Assist Mission Scenarios from Low to High Fidelity

Darcey Graham, Jacob Englander, Nicholas Rattenbury and John Cater*

Gravity assists can provide changes in velocity that the propulsion systems of low-thrust spacecraft may otherwise be unable to produce. Low-fidelity models make approximations to enable the search of a wide problem space. However, this can cause issues when upgrading to high-fidelity, as gravity assist trajectories are sensitive to their initial guess. The widely used zero-sphere of influence patched-conic model performs well for Sun-centered interplanetary trajectories, but less so when upgrading some other systems to high-fidelity. Here, we explore the challenges posed by such upgrades in various mission scenarios and suggest adaptations to the low-fidelity model to combat these difficulties.

09:20 AM

AAS 22-727: Converting Optimal Spacecraft Trajectories: Direct, Many-Impulsive-Maneuver to Indirect, Continuous, Primer Vector Thrust

David Ottesen and Ryan Russell*

Optimal, many-revolution spacecraft trajectories using an indirect method are challenging to solve. The connection is made for a class of models between optimal direct solutions and initial guesses for indirect formulations. For two-body transfers minimizing thrust-acceleration-squared, primer vector theory is used to convert an optimal, direct, many-impulsive maneuver-trajectory to the initial guess for an indirect, continuous-thrust equivalent solution. The mapping algorithm is independent of how the direct solution is obtained, and leverages any Lambert solver and its partial derivatives. The design space is explored and the process is demonstrated for examples using up to 1,000 revolutions.

09:40 AM

AAS 22-759: Advances in Koopman Operator Theory for Optimal Control Problems in Space Flight

Christian Hofmann, Simone Servadio, Richard Linares and Francesco Topputo*

The low-thrust trajectory optimization problem is solved with the Koopman operator theory (KOT). A framework is presented where the original nonlinear dynamics are transformed into a higher-dimensional bilinear system using the KOT and a set of orthogonal polynomials. The nonlinear dynamics are projected onto a set of orthogonal polynomials via the Galerkin method to obtain the evolution of the eigenfunctions, so that the time evolution of any observable is described as a linear combination of the basis functions. The accuracy of the transformed system is assessed, and an example transfer to an asteroid is solved to assess the performance.

10:20 AM

AAS 22-782: Comparison of Indirect and Convex-Based Methods for Low-Thrust Minimum-Fuel Trajectory Optimization

Nicholas Nurre and Ehsan Taheri*

This work presents a comparison between low-thrust minimum-fuel solutions obtained using the indirect method and successive convexification. Convex optimization guarantees convergence of trajectory solutions in polynomial time. However, trajectory optimization problems are often non-convex and must be transformed into convex subproblems and then solved successively to closely approximate the solution to the actual nonlinear problem. An attempt to understand the effect of this approximation in the cost of long-time-horizon transfer problems is performed by using solutions from the indirect method as the optimal baseline. Results show loss in fuel-optimality the longer the time-horizon with possible causes and solutions hypothesized.

10:40 AM

AAS 22-614: A coupled spacecraft system and trajectory optimization framework using GMAT and OpenMDAO

Gage Harris, Ping He and Ossama Abdelkhalik*

We developed an efficient framework to simultaneously optimize the spacecraft system and trajectory using NASA's OpenMDAO and GMAT toolboxes. The objective function was the fuel burn, and the design variables were the engine input parameters (e.g., chamber pressure, expansion ratio), the spacecraft trajectory control parameters (e.g., burn directions, burn times, and time of flight), and the initial fuel mass. The constraints included the final positions and velocities of the spacecraft. We found that the coupled engine and trajectory optimizations obtained 13% to 20% more fuel burn reduction than the trajectory-only optimization with fixed engine parameters.

11:00 AM **AAS 22-835: An adjoint sensitivity method for the sequential low-thrust orbit raising problem**

Adrian Arustei and Atri Dutta*

More geocentric space missions take advantage of the tremendous mass savings provided by solar-electric propulsion. Designing multi-revolution low-thrust trajectories onboard is challenging due to the underlying control problem complexity. The sequential low-thrust orbit-raising problem provides a fast and robust framework to design such trajectories without the need for a user-provided initial guess. This paper improves upon the previous technique by employing a control law parametrization using B-splines and by providing adjoint sensitivities for control parameters. Further additions include extending the planning horizon and targeting non-GEO end states. Using numerical simulations, we illustrate the proposed extensions effect on the transfer times.

11:20 AM **AAS 22-733: Possible Trajectories to Planet Nine**

*James Evans Lyne, Nicholas Powers, Noah Compton, Peyton Franklin and Allison Warren Carroll**

Planet 9 is a large body believed to exist in the outermost part of the solar system hundreds of astronomical units from Earth. A recent study identified the most probable values for five of the planet's orbital elements but not for true anomaly. In the current paper, potential trajectories to Planet Nine are examined. Since true anomaly is unknown, a family of trajectories was simulated, and critical mission parameters were examined as a function of its assumed value. Due to the extreme distances involved, high-thrust architectures using a single gravity assist at Jupiter typically have transit times of sixty years or more.

11:40 AM **AAS 22-739: Preliminary analysis of a fuel station strategy for active debris removal missions in low Earth orbit**

Adrian Barea, Hodei Urrutxua and Luis Cadarso*

This work proposes a two-stage methodology for the preliminary design of active debris removal missions comprising a servicing satellite and a fuel station. The upper stage explores promising values of the station location. The lower stage determines the objects to be removed, the removal sequence and the maneuvers of the servicing satellite so that the aggregated criticality of the selected objects is maximized. This is modelled as a Mixed Integer Linear Programming problem and solved using a branch-and-bound method. Both stages are iterated until the optimal station location is found. Two practical cases involving prominent debris clusters have been analyzed.

Session: Spacecraft Guidance, Navigation, and Control I

Room: Carolina C, Time: 08:00 AM-12:00 PM

Session Chair: John Christian (Georgia Institute of Technology)

08:00 AM **AAS 22-516: Active Terrain Relative Navigation for Lunar Landings**

Po-Ting Chen, Andrew E. Johnson, Timothy Setterfield, Anup Katake, Yang Cheng and Gregory Griffin*

Landing on planetary bodies is an important part of space exploration. Precision landing capability enables a lander to land at a specific location on the planet surface. Terrain Relative Navigation (TRN) is an autonomous navigation technique to achieve precision landing. Passive-TRN based on camera system is proven successful in the Mars 2020 mission. For un-illuminated locations, Active-TRN based on LIDAR sensor is needed to achieve precision landing. In this paper, the performance of Active TRN for lunar landings is investigated using numerical simulations and publicly available altimetry data.

08:20 AM **AAS 22-644: Towards limb-based autonomous navigation and mapping of primitive bodies**

Enrico Zucchelli, Noah Lifset, Brandon Jones, Ryan Russell and Shyam Bhaskaran*

The paper describes a method to estimate visual hull and relative pose of a small celestial body by limb information extracted from images. The scale is not resolved. The shape of the small body is represented with a Gaussian Process, which provides a continuous representation of the surface and corresponding uncertainty.

08:40 AM **AAS 22-657: INITIAL POLE ESTIMATION OF SMALL BODIES ON APPROACH USING INFRARED IMAGERY**

Koundinya Kuppa, Jay McMahon and Ann Dietrich*

Estimating the pole axis of a body is crucial to spacecraft autonomy and shape modeling. Current methods that utilize light curves are very time and resource intensive, and the resultant errors are quite large. Navigation and shape modeling fidelity are affected significantly by this error. In this study, we present a new pole estimation method that utilizes infrared images from a spacecraft on an approach trajectory to a body. The benefit of this approach is that it does not rely on feature tracking, does not require prior knowledge, and only relies on the macroscopic properties of the body.

09:00 AM **AAS 22-592: LiDAR Simulation Considering Target Reflection for Proximity Navigatoin to Non-Cooperative Target**

Yu Nakajima, TAKAHIRO SASAKI and Toru Yamamoto*

LiDAR is one of the key technologies to achieve rendezvous toward non-cooperative targets. However, it is difficult to test on ground. This study proposes a LiDAR simulation approach to verify LiDAR navigation algorithms by generating pseudo-observation data in-orbit. The simulator determines the distance and the signal intensity reflected from a mock target, generating point clouds following LiDAR scanning patterns. The measurement and signal reflection model was constructed from the experiment data. The simulated data were compared to the experimentally obtained data and the results indicated that the simulator generates precise LiDAR measurement, which will contribute to the evaluation of navigation sensors.

09:20 AM **AAS 22-642: Navigation Performance Analysis and Trades for the Lunar GNSS Receiver Experiment (LuGRE)**

Lauren Konitzer, Joel Parker and Nathan Esantsi*

The Lunar GNSS Receiver Experiment (LuGRE) is a joint NASA-Italian Space Agency flight demonstration payload that will fly onboard the Blue Ghost Mission 1 (BGM1) lunar lander to demonstrate multi-GNSS based position, navigation, and timing (PNT) in cislunar space and at the Moon. The payload will receive GPS and Galileo signals to characterize the lunar GNSS signal environment and demonstrate navigation and time estimation to support development of lunar GNSS receivers. This paper investigates key factors of the LuGRE mission design and concept of operations and how they may be exploited to return interesting science.

09:40 AM **AAS 22-746: Invariant Theory as a Tool for Spacecraft Navigation**

John Christian and Harm Derksen*

Many spacecraft navigation algorithms are built upon models describing the geometric relationships between the spacecraft state and the measurement produced by a sensor. This is especially true for vision-based sensors. However, extracting the maximum amount of independent state information from a measurement (or set of measurements) is not always straightforward. This work investigates the utility of invariant theory as a tool to better utilize the information content within sensor data for spacecraft navigation. Direct applications include star pattern recognition, terrain relative navigation (TRN), and LIDAR point cloud registration.

10:20 AM **AAS 22-747: LIDAR Odometry for Lunar Terrain Relative Navigation**

Carl De Vries, John Christian, Mike Hansen and Timothy Crain*

Future missions to the lunar surface are expected to make use of LIDAR sensors for navigation during landing. This is especially true when the lunar landing must be accomplished under undesirable lighting conditions for camera-based navigation. Moreover, when local maps of the lunar terrain are also poor or unavailable to the lander in real-time, concepts from LIDAR odometry (LO) are highly relevant. This work develops an algorithmic framework for LO suitable for supporting future lunar exploration missions.

10:40 AM **AAS 22-751: Crater Navigation with Extended Feature Models**

James Brouk and Kyle DeMars*

Feature-based terrain relative navigation often utilizes natural impact craters to localize as they are abundant natural phenomena, though several critical assumptions are required. This paper presents an extended feature measurement model for crater navigation that models the approximately elliptical extent of natural impact craters as an inverse Wishart distributed random matrix. By accounting for the extent of natural terrain features, a continuum of valid observations can be considered within the filtering solution, relaxing the requirement for exhaustive image-processing and making possible new environmental modeling techniques. Monte Carlo simulation and analysis are utilized to assess the filter's crater state estimation.

11:00 AM **AAS 22-858: Robust Landmark Detection on Small Body Surfaces Using Shadows within Images**

Jacopo Villa, Jay McMahon and Issa Nesnas*

In this paper, we present an algorithm to robustly detect landmarks on the surface of small bodies using shadow observations in onboard images. For these celestial bodies, detecting landmarks from a given catalog is traditionally challenging due to the evolution in lighting conditions and observing geometry, both affecting the appearance of landmarks. Using a probabilistic representation of observed shadow properties, landmarks are detected in the camera plane and their location and elevation on the surface is recursively estimated as more images are processed. We demonstrate performance of this technique using both real and simulated imagery, showing superior performance compared to state-of-the-art visual features.

11:20 AM **AAS 22-537: Model Predictive Control in the Three-Body Problem using Invariant Funnels as Terminal Sets**

Jared Blanchard, Martin Wen-Yu Lo, Damon Landau, Brian Anderson and Sigrid Close*

This paper describes a method for augmenting Model Predictive Control techniques using invariant funnels computed in the Circular Restricted Three-Body Problem. We use ellipsoids that roughly approximate the boundary of the invariant funnel as convex terminal sets for a short look-ahead optimization problem at each time step. We apply this method to a hypothetical low-thrust mission to land on Jupiter's moon Europa and show that including the invariant funnels as terminal sets reduces the amount of control effort required by almost an order of magnitude.

11:40 AM **AAS 22-557: Third Order Repetitive Control: Evaluation of Stability Boundary and Development of Sufficient Conditions**

Ayman Ismail and Richard Longman*

Spacecraft can need method for vibration isolation from slight imbalance in CMG’s. Passive isolation gives imperfect performance. Active feedback control can improve performance. Repetitive Control (RC) adds knowledge that jitter is periodic with a known period, and aims for perfect isolation. Error in the previous period is used to adjust command this period. In some applications, the accuracy of the period knowledge may not be perfect, and the period may fluctuate. New methods are developed here using error from the past 3 periods to improve robustness. Methods developed assess the RC stability boundary and give useful sufficient conditions.

Session: Relative Motion and Formation Flying II

Room: Carolina D, Time: 01:30 PM-04:50 PM

Session Chair: Jennifer Hudson (Naval Postgraduate School)

01:30 PM **AAS 22-511: Calibrated Kalman Filtering in Relative Orbit Estimation**

*Grace Norrix, Eric Butcher and Andrew J. Sinclair**

Kalman filtering has been used with success in relative orbit determination while calibration has been used for both propagation and control of relative orbital motion. The choice of coordinates (Cartesian Hill, spherical, orbit element differences) is critical since the errors associated with linearization differ. This paper develops a calibrated Kalman filter for relative orbit estimation using the equivalence of the linearized dynamics in a given coordinate system as related through linearized transformations. Both spherical coordinates and orbit elements differences are used to develop the calibrated filter in Cartesian Hill frame coordinates, and examples demonstrate the viability of the technique.

01:50 PM **AAS 22-554: Adaptive Neural Network-based Unscented Kalman Filter for Spacecraft Pose Tracking at Rendezvous**

Tae Ha Park and Simone D'Amico*

This paper presents an Unscented Kalman Filter (UKF) based on a Convolutional Neural Network (CNN) to track the pose of a known, noncooperative target spacecraft in close-proximity rendezvous scenarios. The CNN is used to extract the pose-related information from incoming target images. To enable robust pose tracking, the process noise of UKF is adaptively tuned based on underlying orbital and attitude dynamics models. This paper also introduces the Satellite Hardware-In-the-loop Rendezvous Trajectories (SHIRT) dataset which comprises two representative rendezvous trajectories in LEO and two labeled sets of images from different sources to allow testing the filter's robustness across domain gap.

02:10 PM **AAS 22-575: Distributed Absolute And Relative Estimation of Spacecraft Formations**

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

We propose the Distributed Absolute and Relative Estimation (DARE) algorithm for autonomous inertial estimation of spacecraft formations. The algorithm enables each spacecraft to maintain an accurate inertial estimate of the entire formation even in the presence of observability and communication constraints. The algorithm is distributed and scalable to any number of spacecraft in the formation. A modified version of the algorithm called the Sparse Distributed Absolute and Relative Estimation (SDARE) algorithm is also derived. This algorithm is computationally more efficient at the expense of estimation accuracy making it suitable for implementation on nano-satellites where resources are limited.

02:30 PM **AAS 22-726: Simulating a Dynamics-Informed Cislunar RPO Mission Incorporating Orbit Determination**

Nathaniel Kinzly, Benjamin Polzine, Cody Short and James Woodburn*

As the cislunar domain becomes a region of increasing interest among orbit designers, demands for greater understanding of rendezvous and proximity operations (RPO) in the region have increased as well. This paper will present the simulation of a cislunar RPO mission where a chaser satellite enters circumnavigation about a target satellite occupying a halo orbit. The approach and circumnavigation will be informed by the eigendecomposition of the monodromy matrix along the target's halo orbit and the relative orbit determination (OD) conducted by the chaser satellite. The requirement for precise OD under complex cislunar dynamics will present interesting challenges.

02:50 PM **AAS 22-558: COVARIANCE-BASED OBSERVABILITY ANALYSIS METHOD FOR ANGLES-ONLY RENDEZVOUS NAVIGATION**

Moeko Hidaka, Ryo Nakamura and Toru Yamamoto*

In non-cooperative rendezvous, Angles-Only Navigation (AON) is an important navigation method that estimates a relative orbit using the history of target LOS angles and a relative motion model. Ensuring observability is a critical issue for AON, and a new figure of merit is introduced that focuses on the elements of the estimated covariance matrix of AON. The proposed method has the advantage that the sensitivity of the observation error to the estimation error can be evaluated for each element of the relative state vector to be estimated. The numerical simulations based on the typical rendezvous scenarios demonstrate its usefulness.

03:30 PM **AAS 22-828: FPGA Hardware Acceleration for Feature-Based Relative Navigation Applications**

Ramchander Rao Bhaskara and Manoranjan Majji*

An FPGA-based acceleration for feature aided point-cloud registration process is presented for relative navigation applications. A pipelined design for registration using Optimal Linear Translation and Attitude Estimation (OLTAE) algorithm is evaluated on an FPGA fabric while feature correspondence is established on the co-processor of the FPGA-SoC. Using parallelism at the hardware level a reliable platform that is fast enough for relative navigation applications is presented.

03:50 PM **AAS 22-732: Reconstruction of Particle Dispersion Events with Optical Measurements**

*Anonto Zaman and John Christian**

Discrete particle ejection events are known to periodically occur on the asteroid Bennu. Similar phenomena may also occur on other small bodies in our Solar System. If these particle events are observed by the camera aboard an exploration spacecraft, as was the case with the OSIRIS-REx spacecraft during its visit to Bennu, then the apparent motion of particles may be used to reconstruct the event. This work explores the utility of algebraic projective geometry for performing this reconstruction and the resulting algorithms are shown to have many practical advantages when compared to earlier methods.

04:10 PM **AAS 22-769: Tube-Based Nonlinear Model Predictive Control for Robust Autonomous Proximity and Docking Operations**

John Martinez and Hyeongjun Park*

In this paper, a tube-based robust nonlinear model predictive control (TR-NMPC) approach is explored for autonomous rendezvous and docking operations of two spacecraft. Various test cases are considered along with constraints, uncertainties, and disturbances. We explore the development of a controller to handle trajectory generation and translational control for a chaser spacecraft in the approach and docking phase with uncertainties present. TR-NMPC is proposed to achieve safe docking by generating trajectories with various constraints that consist of keep-out-spheres and docking cones. Simulation results demonstrate the capability of the TR-NMPC approach to enforce the constraints while dealing with uncertainties and disturbances.

Session: Machine Learning and Autonomy in Astrodynamics III

Room: Carolina E, Time: 01:30 PM-04:50 PM

Session Chair: Ryne Beeson (Princeton University)

01:30 PM

AAS 22-775: Satellite Detection in Unresolved Space Imagery for Space Domain Awareness using Neural Networks

Jarred Jordan, Daniel Posada, David Zuehlke, Angelica Radulovic, Aryslan Malik and Troy Henderson*

This work utilizes a MobileNetV2 Convolutional Neural Network (CNN) for fast detection of satellites and rejection of stars in cluttered unresolved space imagery. First, a custom database is created using imagery from a ground-based telescope. Images are labeled with bounding boxes over satellites for ``satellite-positive'' images. Then, the CNN is trained on this database and the inference is validated by checking the accuracy of the model on an external data set that was not used for training. The trained CNN provides a method of rapid satellite identification/detection for subsequent use in orbit estimation.

01:50 PM

AAS 22-793: Neural Network for predicting unmodelled dynamics in multi-revolution transfers in Cis-lunar Missions

Yrithu Thulaseedharan Pillay, Matthew Chace, James Steck and Atri Dutta*

Spacecraft trajectory planning often involves optimization using low or medium-fidelity models. The objective of this paper is to use artificial neural networks to capture the unmodeled dynamics in such applications. Specifically focusing on multi-revolution orbit-raising trajectories in cis-lunar space. Considering the circular restricted three-body problem as yielding trajectory estimates and the General Mission Analysis Tool as the high-fidelity environment incorporating true lunar ephemeris and solar radiation pressure, the prediction of unmodeled dynamics in a future revolution is investigated. An iterative technique is presented, along with challenges associated with prediction, and numerical simulations depicting the performance of the designed neural networks.

02:10 PM

AAS 22-713: Comparison of Neural Network Based Satellite Pose Estimation Approaches Using Camera and Lidar Images

Hunter Greenwood and Tae Lim*

To support future autonomous satellite rendezvous and proximity operations, CNN-based pose estimation approaches are studied and compared using 2D camera images and 3D LiDAR point cloud images. To provide meaningful comparison of the two approaches, camera and LiDAR images needed for the CNN training are simulated using the same target satellite and relative range and attitude. The results of this comparative study include image generation processes employed, CNNs selected for 2D and 3D images, training processes, pose estimation accuracy, and discussions on the pros and cons of using either camera or point cloud images.

02:30 PM

AAS 22-813: RGB-D Robotic Pose Estimation For a Servicing Robotic Arm

Jared Herron, Daniel Lopez, Jarred Jordan, Jillian Rudy, Aryslan Malik, Daniel Posada, Mehran Andalibi and Troy Henderson*

A number of robotic and human-assisted missions to the Moon and Mars are in the works. Robotic exploration will be a key component of these missions. The goal of this work is to create a custom Computer Vision (CV) based Artificial Neural Network (ANN) that would be able to identify the posture of a 7 Degree of Freedom (DoF) robotic arm from a single (RGB-D) image - just like humans can easily identify if an arm is pointing in some general direction. ``Sawyer'' robotic arm will be used for developing and training this intelligent algorithm.

02:50 PM **AAS 22-734: A Moon Optical Navigation Robotic Facility on Simulated Terrain: MONSTER**

Francesco Latorre, Andrea Carbone, Sarathchandrakumar Thottuchirayil Sasidharan, Giulia Ciabatti, Dario Spiller, Fabio Curti and Roberto Capobianco*

This work presents MONSTER, a Moon optical navigation robotic facility on simulated terrain, i.e., an experimental facility to simulate lunar navigation problems. The facility consists of a 3D Cartesian manipulator that will be equipped with a spherical joint to simulate both attitude and orbital dynamics. All the experiments that have been performed so far and are planned to be performed are based on innovative and disruptive approaches using artificial intelligence. A crater detection algorithm based on a fully convolutional neural network has been implemented, and a reinforcement learning approach is under development for prescribing the control policy of the simulated system.

03:30 PM **AAS 22-662: AUTONOMOUS RENDEZVOUS AND DOCKING OF SPACECRAFT USING HIERARCHICAL MODEL BASED REINFORCEMENT LEARNING**

Anthony Aborizk, Scott Nivison and Norman G. Fitz-Coy*

This document delineates the proposal and preliminary findings for a model-based reinforcement learning (MBRL) algorithm designed to achieve autonomous rendezvous, proximity operations, and docking (ARPOD). The goal is to improve upon a four phase ARPOD benchmark problem, by customizing a MBRL technique called PETS. Preliminary findings suggests that the MBRL algorithms in question achieve significant sample efficiency but suffer in terms of real time implementation. The following introduces a proposal to include a hierarchical aspect within the controller to improve computation while maintaining sample efficiency.

03:50 PM **AAS 22-633: Instance segmentation for unknown resident space objects inspection missions**

Niccolò Faraco, Michele Maestrini and Pierluigi Di Lizia*

Space missions targeted to the inspection resident space objects are gaining popularity as a tool to enable subsequent active debris removal or other proximity operations. While promising results have already been achieved in the case of cooperative and/or known targets, little has been done in the case of uncooperative and unknown objects. The present work proves the usefulness of machine learning and programmatically generated synthetic images as a tool to aid the research in the field and provide the already existing and future techniques with additional information, in order to make them more robust to off-nominal scenarios.

04:10 PM **AAS 22-562: Optical 6-DOF Guidance and Navigation of an Asteroid Impactor via Meta-Reinforcement Learning**

Lorenzo Federici, Alessandro Zavoli, Andrea Scorsoglio and Roberto Furfaro*

This paper focuses on the autonomous six-degree-of-freedom guidance and navigation of a spacecraft during an impact mission to a binary asteroid system via meta-reinforcement learning. A convolutional-recurrent deep neural network is used as integrated guidance, navigation, and control system, which directly maps optical images collected by the onboard camera to the optimal thrust, thrusting times, and spacecraft spin rate. The objective is to control the camera pointing direction and to maneuver the spacecraft so that it impacts the smaller object of the binary system within a maximum mission time, starting from randomly scattered initial conditions and in the presence of unmodeled dynamics.

04:30 PM

AAS 22-787: Autonomous Low-Thrust Orbit-Raising Using Long Short-Term Memory Neural Networks

Taylor George and Brian Kaplinger*

This paper explores the use of recurrent artificial neural networks with long short-term memory (LSTM) units for the low-thrust, orbit-raising problem. LSTM neural networks can accurately recreate time histories. For optimal control problems, the reduced-order computation of executing the control recreation after the LSTM neural networks are trained could present potential benefits for autonomous use on spacecraft, which may have reduced computational capabilities and resources compared to systems computing the trajectories offline.

Session: Special Session: Juno Mission & James Webb Space Telescope
Room: Carolina A, Time: 01:30 PM-04:50 PM
Session Chair: Thomas Pavlak (NASA / Caltech JPL) and Jeremy Petersen (a.i. solutions)

01:30 PM **AAS 22-599: Juno Orbit Determination and Maneuver Operations: Early Orbit Phase Through End of Prime Mission**
Yu Takahashi, Paul Stumpf, Thomas Pavlak, Matthew Smith, Brian Rush, Dayung Koh, Mark Ryne, Yungsun Hahn, Ramachandra Bhat, Jennie R. Johannesen and Nicholas Bradley*
The Juno spacecraft reached the Jovian system on 05 July 2016 UTC and has been orbiting around Jupiter since then. The prime mission was completed in April 2021 after completing 32 science orbits, and Juno is now in the extended mission phase (currently planned until October 2025). It is the purpose of this paper to summarize our operation experiences and navigation results, as well as our tools developed for precise navigation of the spacecraft in the Jovian environment.

01:50 PM **AAS 22-595: Design and Implementation of the Juno Eclipse Avoidance Maneuver**
Thomas Pavlak, Paul Stumpf, Yungsun Hahn and Ramachandra Bhat*
In the Fall of 2016, a propulsion system anomaly led the Juno Project to cancel the planned Period Reduction Maneuver (PRM) and remain in the 53-day capture orbit indefinitely. This decision forced Juno to traverse a Jovian "eclipse season" to complete its 32-orbit prime mission and put the spacecraft on course for a nearly-12-hour, mission-ending eclipse in November 2019. This paper details the design, implementation, and extensive contingency analysis campaign required to successfully plan and execute Juno's eclipse avoidance maneuver on September 30, 2019 enabling years of additional Juno science operations at Jupiter.

02:10 PM **AAS 22-539: ORBIT DETERMINATION PERFORMANCE OF THE JUPITER ECLIPSE AVOIDANCE MANEUVER BY THE JUNO SPACECRAFT**
Matthew Smith, Yu Takahashi, Brian Rush, Dayung Koh and Rodica Ionasescu*
In the fall of 2019, the Juno spacecraft (s/c) was on a trajectory that would lead to its demise. Were nothing to be done, on October 1, 2019 the Juno spacecraft would incur a mission-ending, ~12-hour solar eclipse due to entering Jupiter's shadow. On that day, a cleverly designed eclipse avoidance maneuver was successfully performed to reorient the orbital plane, allowing us to miss the shadow cone. This paper details the orbit determination (OD) team's preparation for the critical event, and the subsequent analyses done to understand how well the spacecraft performed and where the future of the mission stood.

02:30 PM **AAS 22-598: Juno Extended Mission Trajectory Design**
Thomas Pavlak, Jennie R. Johannesen and Paul Stumpf*
The Juno extended mission trajectory design represents the culmination of an 18-month collaborative effort between the Juno navigation, science, spacecraft, and project management teams. This paper presents the science and trajectory design trades explored and quantifies the Delta-V impacts associated with various options. Strategies for optimizing the equator-crossing longitude grid are also discussed. Ultimately, the Juno extended mission trajectory is enabled by a design methodology yielding four low-altitude Galilean satellite flybys that lower orbital period and dramatically reduce mission Delta-V costs while providing exciting, previously-unanticipated scientific observation opportunities.

02:50 PM

AAS 22-538: ORBIT DETERMINATION PERFORMANCE OF THE GANYMEDE FLYBYS BY THE JUNO SPACECRAFT

Matthew Smith, Yu Takahashi, Brian Rush, Mark Ryne, Dayung Koh and Rodica Ionasescu*

On June 7, 2021 the Juno spacecraft zoomed past Ganymede at an altitude of ~1,050 km, the first of four targeted "close" flybys of a Galilean moon along the newly accepted extended mission (EM) reference trajectory. While monitoring real-time Doppler residuals during the encounter, the orbit determination (OD) team was surprised to see an anomalous signature in the data surrounding the time of closest approach. This paper details the OD team's preparation for the flyby, a first-time event for the mission, and the subsequent analyses to understand the anomaly. We also investigate performance of the following untargeted Ganymede flyby in July.

03:30 PM

AAS 22-611: Flight Dynamics Planning and Operations Support for the JWST Mission

Jeremy Petersen, Karen Richon and Ann Nicholson*

This paper summarizes the flight dynamics support for the James Webb Space Telescope (JWST), including the prelaunch nominal trajectory design, contingency planning for trajectory-related anomalies, and a comparison of the planning to the actual JWST trajectory results. The orbit determination strategy, both planned and executed, will be summarized, and the method of addressing the anomalies as they occurred will be included.

03:50 PM

AAS 22-610: Planning and Execution of the Three Mid-Course Correction Maneuvers for the James Webb Space Telescope

Jeremy Petersen, Karen Richon and Benjamin Stringer*

The James Webb Space Telescope (JWST) was successfully launched on December 25, 2021 12:20 UTC on an Ariane 5 rocket out of Kourou, French Guiana on a direct transfer, low energy manifold transfer out to the Sun-Earth L2 point. Three mid-course correction maneuvers, designated MCC-1a, MCC-1b, and MCC-2, are required to provide the energy necessary to reach L2 due to a purposeful biasing down of the launch vehicle. This paper will document the prelaunch preparation, nominal planning, contingency preparation, and successful execution of the three mid-course correction maneuvers.

04:10 PM

AAS 22-607: Orbit Determination for the James Webb Space Telescope during Launch and Early Orbit

Eric Stoker-Spirt, Jeffrey L Small, Ann Nicholson, Wayne Yu, Arvind Kaushik and Charles Yu*

This paper details several novel challenges encountered in the orbit determination (OD) of the James Webb Space Telescope (JWST) during launch and early orbit. The first OD solution used only 6.5 hours of tracking data, much less than the 24 hours of data usually required for libration orbiters. The observatory area exposed to solar radiation pressure also changed through a series of sunshield deployments while concurrent momentum unloads and attitude telemetry outages occurred. This paper covers how the Flight Dynamics Team prepared for these challenges, how the team handled them on-orbit, and the performance of resulting OD solutions.

04:30 PM

AAS 22-635: JWST Real-Time Mid-Course Correction Maneuver Monitoring Contingency Preparation

Wayne Yu, Taabish Rashied, Antonia Santacroce, Benjamin Stringer and John Lorah*

The NASA James Webb Space Telescope (JWST) mission successfully launched on Dec 25 2021 at 12:20 UTC. During the 30-day transfer to the L2 region, JWST executed three mid-course correction (MCC) maneuvers to insert into a quasi-halo orbit about the Sun-Earth L2 point. This paper covers the design and modeling for these three maneuvers with a focus on the timeline around the execution of each MCC maneuver. It will summarize the actual on-board events as well as the contingency preparation done for maneuver planning, monitoring, and final post burn reconstruction of all three MCC maneuvers.

Session: Asteroid, Earth and Planetary Missions

Room: Carolina C, Time: 01:30 PM-04:50 PM
Session Chair: Isabelle Jean (Canadian Space Agency)

01:30 PM

AAS 22-677: Preliminary Mission Design Tool For Asteroid Tours

Chloe Long, Anivid Pedros Faura, David Lujan and Jay McMahon*

Asteroid tour missions, in which a spacecraft performs flybys of multiple asteroids, allow us to build upon foundational knowledge of our solar system and are of high scientific value. This paper introduces a preliminary mission design tool for finding viable and desirable asteroid tours. This novel tool incorporates a multiple-filter procedure and a modified Rapidly-exploring Random Tree search approach to efficiently construct, evaluate, and compare asteroid tours. The final list of viable asteroid tours is ranked based on user-defined mission constraints such as epoch, time, and propulsive capability. This tool is tested on an example asteroid database.

01:50 PM

AAS 22-788: Assessing the Viability of Refueling at Asteroids on the Way to Mars

Julian Treat and Davide Conte*

ISRU at asteroids can reduce the overall cost of space missions. Candidate asteroids were found by analyzing the inclination, aphelion, and perihelion of asteroids in the solar system. Then, candidates suitable for Earth-Asteroid Mars missions were found using multi-stop Lambert's Problems. Results show that a refueling depot at 2000 SG344 could be accessed using only 3.31 km/s of delta-V and that 2001 AV43 could be accessed with 3.9 km/s of delta-V, far less than the 5.7 km/s minimum for a Mars mission.

02:10 PM

AAS 22-615: Landing Area Analysis for Ballistic Landing Trajectories on the Secondary of a Binary Asteroid

*Iosto Fodde**

The Hera mission plans to release two CubeSats onto the surface of the secondary of the Didymos binary asteroid system. As a ballistic landing trajectory starting from outside the system is used, any uncertainty in the deployment maneuver and in the system parameters will have a large effect on the final landing location. In this work a novel method to find landing trajectories on the secondary that are less sensitive to uncertainties is developed, by using uncertainty propagation techniques to analyse the different possible landing areas. This will allow for the design of robust landing trajectories in binary asteroid systems.

02:30 PM

AAS 22-824: Multiple Observation Opportunities for Trans-Neptunian Objects Part 9: Landing Opportunities

Garrett Bennett, Garett Ball, Rhett Copeland, Samantha Ramsey and James Evans Lyne*

This study is a continuation of previous work by our group investigating mission opportunities to Trans-Neptunian Objects (TNOs). Specifically, the current study seeks to minimize total time of flight to reach the target, while maintaining reasonable hyperbolic excess speeds upon arrival that would make for feasible landing opportunities. Missions to ten TNOs are presented, each of which have reasonable Earth departure C3s, low total mission times of flight, and arrival excess speeds suitable for landing on the on the surface of the respective targets.

02:50 PM **AAS 22-593: Fast Earth-Mars Roundtrip Trajectories to Reduce Health and Safety Risks for Crewed Missions**

Noble Hatten, Kyle Hughes, David Folta and Azita Valinia*

The extended mission duration of a crewed Mars mission compounds integrated risks to crew health and safety. Shortening mission duration would therefore have a direct impact on reducing many human health and performance risk factors. This paper describes trajectory feasibility analyses performed to examine trajectory options for a fast crewed mission to Mars. Studies were conducted to examine options with short overall mission durations (<=400-day roundtrip) and options that focus on minimizing astronaut time in deep space. Trade studies were performed to determine Delta v requirements for a range of launch dates, Mars orbit periods, and Mars stay times.

03:30 PM **AAS 22-831: Trojan Identification, Exploration, Mapping and Reconnaissance Mission**

Dhagash Kapadia, Brian Kaplinger and Zachary Rhodes*

2010 TK_7 is an Earth Trojan asteroid orbiting Lagrange point L4. This asteroid is relatively small, with a diameter of ~300 m, but is thought to contain useful information about the formation of the solar system and the composition of other planetary bodies near close to Earth. This paper details a study to design a small, unmanned spacecraft to orbit the asteroid and achieve basic functional objectives of mapping the asteroid, measuring mass of the asteroid, and analyzing the surface composition.

03:50 PM **AAS 22-672: On the long-term hazardous nature of NEOs**

Oscar Fuentes-Muñoz and Daniel Scheeres*

The asteroid potential Earth collision hazard between is defined by their size and their current Minimum Orbit Intersection Distance (MOID). The MOID is a time-varying quantity that evolves with the heliocentric orbit of the asteroids, they can approach, remain or depart the vicinity of Earth. In this work we characterize the hazardous nature of near-Earth objects by studying the long-term dynamcis of the MOID. Since the orbits of NEOs can become stochastic after a few centuries, we characterize the uncertainty in the predictions. The characterization of the collision probability allows us to discard many asteroids as potentially hazardous.

04:10 PM **AAS 22-718: Use of powered Earth fly-bys to enhance mass retrieval for a two-spacecraft asteroid capture strategy**

Livia Ionescu, Colin McInnes and Matteo Ceriotti*

The capture of near-Earth asteroids in the vicinity of the Earth creates new possibilities for future deep space or crewed missions. Asteroids contain useful resources which can be mined for in-space use. This paper builds on a novel two-spacecraft strategy for asteroid capture missions by investigating the use of powered fly-bys at the Earth to enhance the total asteroid mass retrieved. The model is developed using a patched-conic approach. The retrieved asteroid mass ratio and mission duration are then compared to a strategy using a single spacecraft.

04:30 PM **AAS 22-589: Robust Control for Coupled Orbit-Attitude Motion of Asteroid Probes**

Jinah Lee and Chandeok Park*

This study proposes a design method and a robust controller for the coupled orbit-attitude motion of asteroid probes with reaction wheels as actuators. The proposed example control system can deal with the interactions caused by the actuators. Its users may tune the Lyapunov function to satisfy specific control objectives. The proposed controller is proven to be almost globally asymptotically stable in the sense of Lyapunov. Numerical simulations reveal the effects of unwanted movements arising from the properties of the example controller and the interactions between orbit and attitude.

Wednesday, August 10

Session: Space Domain Awareness II

Room: Carolina D, Time: 08:00 AM-12:00 PM
Session Chair: Brandon Jones (The University of Texas at Austin)

08:00 AM **AAS 22-634: Dynamics-Based Uncertainty Propagation with Low-Thrust**

Michele Maestrini, Andrea De Vittori, Pierluigi Di Lizia and Camilla Colombo*

In recent years low-thrust propulsion has become a viable solution for small satellites operating in LEO. Despite the effort devoted to designing guidance algorithms for such platforms, only few works tackled the problem of estimating their collision probability, which is strongly affected by the thruster uncertainties. To tackle this challenge this work proposes two strategies to provide accurate uncertainty prediction under low thrust. These techniques have been developed in the framework of ESA funded ELECTROCAM contract and they rely on mixing Gaussian Mixture Models to represent uncertainties with Differential Algebra to propagate them.

08:20 AM **AAS 22-505: Covariance Prediction with a Polynomial Model**

Jonathan Aziz, Felix R. Hoots and William Todd Cerven*

The location of a satellite in space is typically described by an element set or state vector at some epoch time and the location uncertainty is described by a covariance. The probability density function is usually assumed to be Gaussian. Nonlinearities can introduce significant errors in the propagation of the covariance, which has been a recurring area of research. We developed a method to remove most of the nonlinearities and accurately propagate the uncertainty estimate for 30 days or more. The accuracy of the predicted uncertainty estimate is within a few percent when compared to Monte Carlo simulation

08:40 AM **AAS 22-817: Covariance based Track Association with Mean and Osculating Modified Keplerian Elements**

Woosang Park and Kyle T. Alfriend*

This paper analyzes how the dynamic nonlinearity of the modified Keplerian element affects the performance of covariance-based track association in long-term orbit propagation. In addition to the regular Keplerian elements, the modified Keplerian elements include a mean motion (n) instead of a semi-major axis (a). Qualitative and Quantitative numerical simulations will be performed to show the efficacy of mean elements compared to osculating elements. It is expected that using the mean modified Keplerian elements is more effective than the osculating modified Keplerian elements to slow the degradation of the cumulative distribution function of the Mahalanobis distance.

09:00 AM **AAS 22-546: A Modified Weighting Scheme for the Automatic Tasker of Space Surveillance Network**

Junling Wang, Xiaoyu Zheng, Jiakang Shen, Jian Huang and Pengyuan Li*

Improving the observation efficiency of sensors can alleviate the strain of Space Surveillance Network (SSN). We provide a modified weighting scheme for observation scheduling of ground-based radars of automatic tasker of SSN. We analyze the influence of observation geometry, observation time and observation distribution in scheduling time span on orbit determination accuracy based on the covariance of relative orbit uncertainty in satellite orbit determination, and then provide a weighting scheme of the SSN automated tasker for SSN to improve the observation efficiency. Finally, the feasibility of this weighting scheme under limited resources is simulated and compared with the reported ones.

09:20 AM

AAS 22-574: Light Curve Inversion for Reliable Shape Reconstruction of Human-Made Space Objects

Liam Robinson and Carolin Frueh*

Characterizing unknown space objects is a growing field of study in Space Domain Awareness. A fundamental measurement used for characterization is the light curve: a set of brightness measurements over time. If the attitude profile and material properties of an object are known, its shape can be estimated in a process called light curve inversion. This work seeks to strengthen and extend current techniques to non-convex objects that can cast shadows on themselves, a class not handled by previous methods. Tools from geometry processing and computer graphics are employed to detect, locate, and introduce simple concavities.

09:40 AM

AAS 22-586: Processing Space Fence Radar Cross-Section Data to Produce Size and Mass Estimates

Luis Baars and Doyle Hall*

With the addition of the Space Fence (SFK) radar to the Space Surveillance Network (SSN), the NASA Conjunction Assessment Risk Analysis (CARA) team now has access to radar cross-section (RCS) measurements for many Earth orbiting satellites. The CARA team has developed a process to estimate satellite sizes and masses from the SFK RCS measurement data. This study describes the processes used to filter the RCS data, defines the algorithms used to estimate satellite sizes and masses, and presents comparisons of estimated values against known nanosat sizes and masses.

10:20 AM

AAS 22-649: Real-Time Image Processing Implementation for On-Board Object Detection and Tracking

MOHAMED SALIM FARISSI, Marco Mastrofini, Ivan Agostinelli, Fabio Curti, Luigi Ansalone, Claudia Facchinetti and Gilberto Goracci*

Resident Space Objects monitoring is crucial for many projects in the framework of Space Situational Awareness and Space Surveillance and Tracking. The Star sensor image on-board Processing for orbiting Objects deTection (SPOT) fits in this field by providing an innovative space-based autonomous solution for objects detection using star trackers. This system is planned for an In-Orbit Validation activity in the near future. The purpose of this paper is to show the SPOT Software / Hardware co-design methodology and efficient real-time implementation on a Zynq platform, which accelerates the processing time by 20 compared to a software solution on the Intel CPU.

10:40 AM

AAS 22-785: Coordinate choice implications for uncertainty propagation in the CR3BP framework

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

This paper employs the Conjugate Unscented Transform technique to accomplish uncertainty propagation using an alternate dynamical model of the Circular Restricted Three Body Problem (CR3BP). The dynamical model introduced in this work is particularly advantageous for long term propagation, since the Jacobi constant (C) is forced to be invariant in the numerical propagation. The fluctuations in C over an extended propagation time in the traditional Cartesian model are outlined, and a case is made for the use of the proposed model for uncertainty propagation in the CR3BP.

11:00 AM **AAS 22-842: Parallelization Techniques for Quantifying Uncertainty Using Embedded Hardware**

Hunter Quebedeaux, Bennie Lewis and Tarek Elgohary*

Quantifying uncertainty is an important issue in astrodynamics and space situational awareness to capture estimates of resident space objects' states; one algorithm of interest is based on orthogonal polynomial approximation (OPA). While OPA provides large improvements compared to traditional Monte Carlo methods, this algorithm is still computationally ineffective in higher dimensional problems and in real time probability estimates. This work aims to further optimize the OPA algorithm by utilizing the GPU accelerated computation of NVIDIA hardware. We utilize the computational effectiveness of CUDA processing to accelerate this task and decrease computational cost of up to three times.

11:20 AM **AAS 22-602: Detecting Space Objects with Binary Wide Field Of View X-Ray Sensing**

Andrea Lopez, Julian Hammerl and Hanspeter Schaub*

Passive detection of objects about a spacecraft is beneficial for a variety of applications, including collision avoidance, proximity operations or relative navigation. The x-ray spectrum generated from ambient space environment electrons impacting an object's surface provides the means for detecting the object over a range of distances depending on local plasma properties. This work investigates the use of a wide field of view x-ray detector solution, mounted on a rotating platform, to detect and track objects in the vicinity of a spacecraft. Acquisition/loss of signal events are used to provide a least-squares solution for the heading of the incoming signal.

Session: Relative Motion and Formation Flying III

Room: Carolina E, Time: 08:00 AM-12:00 PM

Session Chair: John Kidd (Ascending Node Technologies, LLC)

08:00 AM **AAS 22-565: Low Thrust Trajectory Design Using A Semi-Analytic Approach**

Madhusudan Vijayakumar and Ossama Abdelkhalik*

The optimization of continuous-thrust trajectories is complex, time consuming and extremely sensitive to initial guesses. Hence, generating approximate trajectories that can be used as reliable initial guesses in trajectory generators is essential. This paper presents a semi-analytic approach for the design of both planar and three-dimensional trajectories using Hills equations for a constant thrust acceleration magnitude. The proposed equations are employed in a Nonlinear Programming Problem (NLP) solver to obtain the thrust directions. Their applicability is tested for design scenarios like orbit insertion and rendezvous. The trajectory solutions are then validated as initial guesses in high fidelity optimal control tools.

08:20 AM **AAS 22-581: Closed-form Optimal Solutions for Propulsive-Differential Drag Control of Spacecraft Swarms**

Matthew Hunter and Simone D'Amico*

This paper presents a novel optimal control approach for Distributed Space Systems (DSS) to minimize the total delta-v cost for large, time-constrained reconfigurations. Reconfiguration cost is decreased by blending differential drag and propulsive control within the same control window. By parameterizing the problem with Relative Orbital Elements (ROE) and leveraging reachable set theory, maneuver planning methodology is derived to produce provably-optimal, full rototranslational control solutions in closed-form, such that they can be implemented on hardware-limited spacecraft.

08:40 AM **AAS 22-650: Nonlinear Dynamics and Control of J2 and Drag Perturbed Spacecraft Formation Flying via SDRE Technique**

*Ayansola Ogundele**

The State-Dependent Riccati Equation (SDRE), a well-known technique that is related to the Riccati equation for linear systems, provides an effective algorithm for synthesizing nonlinear feedback controls. In this paper, the SDRE technique is employed for the design of nonlinear control of the J2 and drag perturbed spacecraft relative motion. Firstly, a nonlinear dynamic model of spacecraft formation flying under the effects of J2 and atmospheric drag is developed. Afterward, the dynamic equation was modeled into state-dependent coefficient (SDC) parameterized forms suitable for the application of the SDRE technique. Via numerical simulations, the effectiveness of the SDRE controller was demonstrated.

09:00 AM **AAS 22-710: Relative Guidance, Navigation and Control in Multibody Gravitational Regimes**

*Fouad Khoury and Corinne Lippe**

This work seeks to develop and implement relative motion guidance, navigation and control strategies for the purposes of coordinating spacecraft in chaotic multibody gravitational systems. Specifically, this investigation centers on cislunar applications by demonstrating a variety of relative motion scenarios along the following non-Keplerian orbits: a $\mathbf{L_1}$ Halo, a 9:2 $\mathbf{L_2}$ Near Rectilinear Halo Orbit (NRHO) and $\mathbf{L_2}$ Halo.
First, a framework to characterize the relative dynamics in a target spacecraft's LVLH frame is presented. Once the dynamics and their linearized form are validated, the dynamical model is implemented to demonstrate orbital rendezvous, spacecraft loitering,

and relative navigation along each of the abovementioned orbits in a target-chaser configuration.

09:20 AM **AAS 22-802: Computation of Relative Orbital Motion Using Product of Exponentials Mapping**

Aryslan Malik, David Canales Garcia, Taylor Yow, Daniel Posada, Christopher Hays, David Zuehlke and Troy Henderson*

The Product of Exponentials (PoE) method consists of an exponential mapping based on screw theory, used in robotics. However, it can easily be adapted to describe the position and orientation of any body in relation to another body or frame. In prior work, it was demonstrated that the PoE framework is useful as an alternative method for defining and drawing orbits given a set of orbital elements. This paper expands the application of the PoE framework to compute relative orbital motion. This novel formulation is proven to efficiently correlate the relative attitude and position between a chaser and a target.

09:40 AM **AAS 22-515: Autonomous Phasing Maneuvers in Near Circular Earth Orbits**

Davide Costigliola and Lorenzo Casalino*

This work addresses the problem of the impulsive planar reconfiguration of the relative motion in near circular Earth orbits, when the relative motion change is dominant in the along-track direction.

The problem is formulated in terms of relative orbital elements.

Maneuvers consist of three impulses and they are obtained analytically, with their corresponding application times, based on physical insights. The problem is quadratic and this solution is then used to find the optimum by analytically solving the Karush-Kuhn-Tucker system of equations.

It is shown by simulation results that propellant consumption losses are always below the 4.5% of the actual global optimum.

10:20 AM **AAS 22-664: Astrodynamics-Informed Sparse Kinodynamic Motion Planning for Safe Relative Spacecraft Motion**

Taralicin Deka and Jay McMahon*

The authors of this paper have previously developed an algorithm for fuel-efficient and collision-free spacecraft relative motion planning, called the Astrodynamics informed kinodynamic motion planning (AIKMP) algorithm. In this paper, they propose to extend the application of the AIKMP algorithm to a perturbed environment. They will use a linearized lambert solution and an additional tree-pruning method to make the algorithm more suitable for efficient relative motion planning for astrodynamics applications with non-Keplerian dynamics. The resulting algorithm will have widespread applications ranging from collision-free spacecraft formation flying to spacecraft proximity operations.

10:40 AM **AAS 22-700: Autonomous Rendezvous With Small Temporarily Captured Orbiters**

Shota Takahashi, Daynan Crull, Lisa Whittle and Daniel Scheeres*

Temporarily Captured Orbiters (TCOs) are attractive candidates for asteroid retrieval and In-Situ Resource Utilization (ISRU). This paper studies the feasibility of applying the autonomous navigation and guidance scheme proposed previously by the authors for larger heliocentric asteroids to the proximity operation of TCO rendezvous missions, using 2006 RH120 as an example target. Unlike rendezvous with heliocentric asteroids, the motions of TCOs are under the strong influence of Earth's gravity. Relative motion dynamics are derived, and the effect of ephemeris errors is analyzed. End-to-end simulations that combine both onboard navigation and guidance are performed, which shows the approach is feasible.

11:00 AM **AAS 22-691: Fast Approximation of Continuous Thrust Optimal Relative Control in the Three Body Problem**

Jackson Kulik, Dmitry Savransky and William Clark*

Using first and second order variational equations as well as cocycle properties associated with an indirect optimal control problem, we may precompute and interpolate state transition tensors about a given reference trajectory of a dynamical system. We apply this to the approximate solution of continuous thrust optimal control of satellite relative motion in the three body problem. Arbitrary relative transfers near some reference orbit are approximated without requiring numerical integration each time the boundary conditions or their timing are adjusted. This approach enables fast computation in trajectory and mission design.

11:20 AM **AAS 22-685: Resilience of Orbital Inspections to Partial Loss of Control Authority of the Chaser Satellite**

Jean-Baptiste Bouvier, Robyn Woollands, Himmat Panag and Melkior Ornik*

We present a new methodology to perform safely an inspection mission by a spacecraft enduring actuation delay and a loss of control authority over one of its thrusters. To prevent this malfunctioning chaser satellite from breaching the keep-out sphere around the target satellite, we calculate its maximal stopping distance and use resilience theory. We employ a convex solver to generate a safe minimal-fuel reference trajectory to perform the inspection mission. Then, relying on state prediction, adaptive trajectory tracking and PID control the malfunctioning spacecraft is able to follow the reference inspection trajectory.

Session: Trajectory, Mission, and Maneuver Design and Optimization IV

Room: Carolina A, Time: 08:00 AM-12:00 PM

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

08:00 AM

AAS 22-804: Preliminary Mission Design for the Interhemispheric Conjugacy Explorer Concept

*Brian Kaplinger**

Most models for solar wind interactions with Earth's upper atmosphere are based on a process known as the Dungey cycle, which predicts symmetric magnetic field behavior at the north and south magnetic poles (NH/SH). However, data have shown evidence of asymmetric behavior since at least 2002, but only one simultaneous space observation was conducted in 2009. This paper presents a dedicated mission concept that includes synchronized NH/SH observations of auroral activity with conjugate measurements taken in-situ in low-Earth orbit.

08:20 AM

AAS 22-639: Trajectory Design for a Secondary Payload within a Complex Gravitational Environment: the Khon-1 Spacecraft

Alexander Hoffman, Beom Park, Kathleen C. Howell, Shaun Stewart and Timothy Roorda*

Secondary payloads provide lower-cost mission opportunities to the Moon, which continues to be an important target for future space missions. Intuitive Machines' Khon-1 mission is one such example, planned to launch in 2023 to provide communications to the lunar surface. The trajectory design for the mission is associated with demanding challenges: the limited propulsive capabilities necessitate the exploitation of the Sun's gravity while the mission timeline must accommodate adjustments to the primary mission. In response to this problem, a rapid trajectory design process using various dynamical models and tools is developed and applied successfully for contingency launch dates.

08:40 AM

AAS 22-697: Contingency Analysis and Recovery Planning for the Korea Pathfinder Lunar Orbiter

Stephen West, Tiffany Finley, Craig Nickel, Mike Loucks, John Carrico, Jae-ik Park and Jun Bang*

The Korea Pathfinder Lunar Orbiter (KPLO), South Korea's first lunar mission, will enter lunar orbit in December 2022. After launch from Cape Canaveral Space Force Station, KPLO will follow a ballistic lunar transfer prior to insertion into a 100-km circular polar lunar orbit for a nominal one-year science mission. We performed a sensitivity analysis on the baseline trajectory to identify potential contingency scenarios. For each trajectory contingency case, we developed a mitigation strategy and simulated multiple recovery trajectories that satisfy mission requirements. The results of this study inform operational planning for KPLO and demonstrate the robustness of the nominal trajectory.

09:00 AM

AAS 22-623: James Webb Space Telescope Trajectory, Communications, and Instrumentation Comprehensive Analysis

Pedro J. Llanos and Attila Matas*

This paper highlights the main aspects of the trajectory analysis, communications, and instrumentation thermal profiles for the James Webb Space Telescope mission. The trajectory analysis is performed using the CRTB problem and the JPL Ephemeris, and the corresponding station-keeping maneuvers to keep the telescope in a Lissajous orbit around the Sun-Earth L2 point. General characteristics of the communication, and thermal instrumentation systems during the transfer phase and orbit phase around L2 is provided, including the signal-to-noise ratio, DSN antenna usage, azimuth-elevation profiles, DSN down power received and up power transmitted, range and range rate

09:20 AM **AAS 22-725: Analysis of the Approach Direction of the Human Landing System to a South Pole Landing Site Subject to Lighting and Communication Constraints**

Laura Burke, Anthony Genova, Bharat Mahajan and Min Qu*

The Human Landing System (HLS) baseline mission design utilizes a Near-Rectilinear Halo Orbit (NRHO) as the staging orbit for crewed missions to the lunar surface. Libration of the Moon causes the South Pole to shift beneath the NRHO leading to variation in the nominal HLS approach path to the surface to maintain near in-plane alignment of the NRHO, LLO, and approach phase. Solar and Direct-to-Earth (DTE) availability during the approach phase varies from landing opportunity to landing opportunity. Maintaining DTE line-of-sight communication and suitable illumination conditions for optical Terrain Relative Navigation (TRN) and crew visual awareness during terminal descent will require modification to the nominal approach azimuth for some landing opportunities.

09:40 AM **AAS 22-709: Minimum-Fuel LEO-to-HEO Orbit Transfer Using Multi-Domain Gaussian Quadrature Collocation**

Brittanny Holden and Anil Rao*

A numerical optimization study of minimum-fuel Earth-based orbital transfers from low-Earth orbit (LEO) to high-Earth orbit (HEO) is performed. Various values of maximum allowable thrust acceleration are considered. A key aspect of the study performed is that the optimal thrusting structure is not assumed to be known a priori, but is determined as part of the solution process. In order to determine the optimal thrusting structure, a recently developed bang-bang and singular optimal control (BBSOC) method is employed together with multiple-domain Legendre-Gauss-Radau quadrature collocation. Key results obtained include the number of switches in the optimized thrust and the total impulse.

10:20 AM **AAS 22-683: Radial Optimal Control Software (ROCS): An Adaptive Solver Based on Radial Basis Functions**

*Bethany Kelly, Ahmed Seleit and Tarek Elgohary**

In this work, we introduce a user-friendly MATLAB toolbox called Radial Optimal Control Software (ROCS) to solve nonlinear optimal control problems. The solver is based on indirect methods where necessary conditions are derived and discretized. Radial Basis Functions (RBFs) are used to approximate Two-Point Boundary Value Problems (TPBVP) because they are nodal-distribution independent, making the solver efficient with path constraints. ROCS displays high computational speed, accuracy and continuous representation of states and control. This is demonstrated by comparing the results from benchmark problems- Zermelo's problem, duffing oscillator, and a planar orbit transfer problem- to exact solutions and other numerical solvers.

10:40 AM **AAS 22-823: Vectorized Trigonometric Regularization for Optimal Control Problems with Singular Arcs**

Yevhenii Kovryzhenko, Ehsan Taheri and Keziban Saloglu*

This work considers an alternative derivation of control vector for problems with singular control arcs. As an application, we consider the classical Goddard rocket maximum ascent problem with bounded control and path constraints. The nature of problem leads to Bang-Singular-Bang control arcs, which pose numerical issues due to discontinuities in the optimal solution, and more importantly, the presence of singular control arcs. For bounded control, we use traditional smooth regularization method combined with a trigonometric regularization method to obtain the optimal control without any alterations to the system dynamics and the need of choosing the optimal control.

11:00 AM **AAS 22-830: Nonlinearity Index for State-Costate Dynamics of Optimal Control Problems**

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

The nonlinearity index has been developed as a metric to quantify the degree of nonlinearity of a dynamical system and how the selection of coordinates plays a role in it. This paper extends the application of the nonlinearity index to augmented state-costate dynamical systems that result from indirect optimal control methods. The proposed state-costate index provides a measure of how nonlinear the resultant dynamics and control mapping are for a problem posed in a given coordinate set. Some classical coordinate sets along with a recently introduced quarternion based orbital element sets will be explored in the context of trajectory optimization.

11:20 AM **AAS 22-856: Interplanetary Ballistic Multiple Gravity Assist Patched Conics Mission to Neptune**

Dhagash Kapadia and Brian Kaplinger*

This study documents four near-ballistic multiple gravity-assist (MGA) trajectories from Earth to Neptune from the years 2021-2051 and identified potential launch vehicles to place a spacecraft into a geostationary transfer orbit (GTO) to each of the MGA trajectories. This study analyzed feasible launch velocities and total ΔV less than 6 km/s. All the trajectories analyzed include the braking maneuver necessary to capture and park in Neptune's circular orbit. All documented trajectories have a launch window between 2021 and 2030, and provide detailed information about potential launch dates for a Neptune mission.

11:40 AM **AAS 22-729: Trajectory Design for a Spacecraft Capable of Deploying Probes to the Martian Surface en route to Low Mars Orbit**

Anthony Genova, Dylan Morrison-Fogel, Andres Dono and Alan Cassell*

The presented trajectory design and analysis was performed for the *Aeolus* spacecraft mission concept. The Aeolus spacecraft consists of an orbiter (i.e., "mothership") with the goal of transferring from Earth to low Mars orbit via propulsive and/or atmospheric braking (i.e., aerobraking). During various phases of flight from hyperbolic approach of Mars through low Mars Orbit, the Aeolus orbiter will deploy multiple probes which are targeted to land on the Martian surface with the goal of achieving global surface coverage.

Session: Orbit Determination and Space Surveillance Tracking II

Room: Carolina C, Time: 08:00 AM-12:00 PM
Session Chair: Siamak Hesar (Kayhan Space Corp)

08:00 AM **AAS 22-626: Short-arc Optical Data Processing**

*Gim Der**

This paper presents a new initial orbit determination (IOD) algorithm to deduce a reasonable initial state vector at any orbit altitude for differential correction (DC) optical data processing. Recent advances of optical systems and tracking techniques allow short-arc data collections for Near-Earth objects, but they often lead to failures in using Gauss and Laplace angles-only IOD algorithms. By varying the radius of a circular orbit and comparing the residual angles of the observed-minus-computed angles between the first and last observation times, a reasonable IOD state vector can be initiated to a DC algorithm for further improvement.

08:20 AM **AAS 22-629: Transitioning from Extent Estimation to Individual Tracking Following an Orbital Break-up Event**

Melissa Adams and Liam Healy*

The goal of this research is to track a cluster of objects following a breakup event in Earth orbit, such as the resulting dispersion of debris after a collision, or small satellites after a mass launch. The expected results will culminate in a set of algorithms that will be able to start tracking a tight cluster of objects as a single target with extent and efficiently track the dispersion of these objects, finally resulting in separate tracks for each individual object.

08:40 AM **AAS 22-686: Astrodynamics Algorithms for Rapid Space Catalog Building**

*Gim Der**

This paper presents seven Vinti-based astrodynamics algorithms for rapid Space Catalog building. The traditional SGP4-based algorithms have demonstrated their usefulness for catalog maintenance, but the rapid increase in small satellite and space debris populations, and the resulting millions of radar and optical observations per day, call for innovative analytical astrodynamics algorithms for perturbed orbit propagation, initial orbit determination (IOD) and differential correction (DC), with focus on the processing of uncorrelated target (UCT) observations. Using over 100 numerical examples of real-world radar and optical data, the seven Vinti-based astrodynamics algorithms demonstrate good performance and realistic results.

09:00 AM **AAS 22-630: Long-Term Cislunar Surveillance via Multi-Body Resonant Trajectories**

Maaninee Gupta, Kathleen C. Howell and Carolin Frueh*

In the coming decades, numerous spacecraft are expected to populate cislunar space, reaching beyond GEO and out to the lunar vicinity. The complex cislunar dynamical environment necessitates the use of new and unique orbits for sustaining long-term operations via space domain awareness. In this investigation, resonant orbits are incorporated into the trajectory design process to expand the range of cislunar trajectories for surveillance. The properties of the proposed itineraries facilitate their long-term viability, which is further validated in a higher-fidelity ephemeris model. Constellations of spacecraft in resonant orbits offer a promising catalog of trajectories for space-based sensors.

09:20 AM

AAS 22-799: Approximating Admissible Control onto the Cislunar Highways for Detection and Tracking of Spacecraft

David Schwab, Roshan Thomas Eapen and Puneet Singla*

There exists a need to expand current Space Domain Awareness (SDA) architectures to account for additional challenges present in cislunar space. A scenario of particular importance is the ability to define a useful search space if custody of a cislunar spacecraft has been lost. Invariant manifold structures present in the dynamics of the circular three-body problem (CR3BP) define highways in which spacecraft must reside to transit to different regimes of the CR3BP. This paper aims to approximately define admissible controls which will enter a spacecraft onto these highways and use this estimate to define an intelligent search space.

09:40 AM

AAS 22-814: Orbit Determination Using Ground- and Space-Based Measurements for Space Traffic Management

Jacob Stratford, Paul J. Cefola, David Gondelach, Stefan Frey and Juan Félix San-Juan*

Space Based Visible (SBV) telescopes complement the observability offered by ground-based telescopes resulting in the possibility of continuous tracking of space objects. This work develops and demonstrates a standalone orbit determination program that can process a mixture of ground-based and space-based measurements. We base our system on the GTDS orbit determination program. We demonstrate the system using both simulated and real data test cases. The real data cases employ astrometric observations made by the NEOSSat Space-Based SSA Microsatellite Mission. Residual errors from the orbit determination are in accord with the established error budget for the NEOSSat space-based measurements.

10:20 AM

AAS 22-780: Optimized Cislunar Space Domain Awareness using Bi-Circular Restricted Four Body Dynamics

Surabhi Bhadauria, Carolin Frueh and Kathleen C. Howell*

The increasing number of launches around the Moon has generated a need to surveil the cislunar space for active utilization of space. Tracking and detection techniques from the Near-Earth region cannot be directly applied to cislunar space objects due to multi-body dynamics and expansion in volume of space. In this paper, the geometry of bi-circular four body problem is used to derive an expression for finding the visibility instead of calculating it for each location in space and to generate a map of visible locations in cislunar space given the geometry and reflective properties of an object.

10:40 AM

AAS 22-786: Orbit Characterization and Determination Strategies in the CR3BP Framework

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

The usefulness of existing architectures for Space Domain Awareness (SDA) diminishes greatly in the neighborhood within cislunar space. With proposed expansions of activities, traditional SDA approaches must adapt with newer tools. This paper investigates two orbit characterization strategies that rely on leveraging analytic formulations in the vicinity of Earth-Moon Lagrange points: (1) using Richardson's variables to characterize halo orbits through reduction to the center manifold, and (2) using action-angle variables from normal-form approximations of the CR3BP Hamiltonian. The action-angle variables are proposed as orbital-element alternatives for the CR3BP. The utility of the proposed strategies are demonstrated through orbit determination examples.

11:00 AM **AAS 22-714: DATA ASSOCIATION FOR MANEUVERING SPACE OBJECTS CONSIDERING DIFFERENT CONTROL DISTANCE METRICS**

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

When radar or optical tracks are far from the set of known targets, they may correspond to a new object (recently launched or generated from a collision or break-up event) but also to a maneuvered object. Within this work we propose the use of different control distance metrics, tailored to various types of propulsive systems, in order to provide a better dynamical insight for post-maneuver data association. Impulsive and low-thrust control distance metrics can be used to resolve track association ambiguitiy given prior knowledge on the object: thrust level for electric propulsion and maneuver history for chemical engines.

11:20 AM **AAS 22-659: MULTIDUAL AND DUAL LIE ALGEBRA REPRESENTATIONS OF HIGHER-ORDER KINEMATICS**

*Daniel Condurache**

In this paper, a computing method for the higher-order acceleration vector field properties in general rigid body motion and multibody system is proposed using algebraic properties of dual and multidual number algebras. The higher-order accelerations field of a rigid body in a general motion is uniquely determined of higher- order time derivative of a spatial twist. For the relative kinematics in multibody systems, equations that allow the determination of the higher-order order acceleration vector field are given, using an exponential Brockett-like formula in these algebras. This is obtained with no need for further differentiation of the body pose with respect

11:40 AM **AAS 22-753: Utilizing Space-Based Observers to Expand Optical Space Surveillance Detection Capabilities**

Alaric Gregoire, Brian Gunter, Gregory Badura and Christopher Valenta*

The use of optical space-based observers (SBOs) to compliment o ground systems is examined for triangulation-based initial orbit determination (IOD). SBOs are simulated in several orbit regimes with a Monte Carlo simulation and have target re-acquisition performance compared against those from traditional optical ground stations. Results indicate the addition of SBOs provide half the IOD opportunities relative to a ground station pair, but improve reacquisition capabilities by an order of magnitude. Considering best-case apparent magnitudes, 30% to 90% visibility for low Earth and geosynchronous orbits respectively, the geosynchronous transfer orbit (GTO) was determined to be the most robust solution for small SDA network extension.

Session: Orbital Dynamics, Perturbations, and Stability

Room: Carolina D, Time: 01:30 PM-04:30 PM

Session Chair: Roshan Thomas Eapen (The Pennsylvania State University)

01:30 PM

AAS 22-728: Investigating Solar Radiation Pressure Modeling for Operations in Near Recilinear Halo Orbit

Clark Newman, Diane Davis and Emily Zimovan-Spreen*

NASA's Gateway program will build a crew-tended station in an Earth-Moon Near Rectilinear Halo Orbit (NRHO). Deep space operations differ considerably from Low Earth Orbit (LEO) operations in the environmental modeling, orbit geometry, and times of flight in the NRHO and during transit. The cislunar environment, as opposed to the LEO environment, lacks atmospheric drag and is simultaneously affected by the gravity of both the Earth and the Moon, and solar radiation pressure (SRP) has a significant effect. This paper investigates the impacts of different SRP models on prediction accuracy, attitude control accuracy, orbit determination performance, and computational burden.

01:50 PM

AAS 22-715: A New Model for the Planetary Radiation Pressure Acceleration for Solar Sails

Livio Carzana, Pieter Visser and Jeannette Heiligers*

This paper provides a novel and detailed analytical model for the Earth's blackbody and albedo radiation pressure accelerations acting on a perfectly reflecting solar sail, valid for any orbital altitude. The assumptions and full derivation of the model are described, its validation against a range of other analytical and numerical approaches is discussed, and its accuracy quantified. Ultimately, results from analyses for NASA's ACS3 solar-sail mission are presented. These show the non-negligible effect of uncontrolled planetary radiation pressure acceleration on the orbit raising capabilities of solar sails in LEO, which yields losses in the altitude gain of 16.5% of the total gain.

02:10 PM

AAS 22-606: CubeSat Orbit Insertion Maneuvering Using J2 Perturbation

*M. Amin Alandihallaj and M. Reza Emami**

A key challenge for inserting a CubeSat into a designated orbit precisely is the fuel scarcity onboard, which strictly constrains large maneuvers, and thus only allows for limited orbit corrections. The paper proposes a maneuvering sequence for setting a CubeSat in low-Earth orbit on a precise trajectory to reach its designated orbital elements precisely by employing the $J2$ perturbation, through which the total required ΔV for correcting the orbit deviation can be reduced considerably. The effectiveness of the proposed approach is investigated through several case studies using numerical simulations.

02:30 PM

AAS 22-692: Time-Varying Perturbation Model Identification in the Neighborhood of CR3BP Periodic Orbits

Matthew Brownell, Puneet Singla, Roshan Thomas Eapen and Damien GUEHO*

The main focus of this work is to find a linear, time-varying model to capture the dynamics of periodic solutions in the vicinity of Lagrange points in the Earth-Moon system via position and velocity measurements. This is motivated by a need for station keeping in said orbits. Rather than finding a global model between input and output space, subspace methods for linear system identification will be utilized to find a subspace over which the unknown dynamics evolve. This identification method allows one to obtain a simplified, linear model that deals with dominate dynamics of the system, and subsequently apply known

02:50 PM **AAS 22-832: On Equinoctial Elements and Rodrigues Parameters**

Joseph Peterson, John L. Junkins and Manoranjan Majji*

The origin and geometric interpretation of the equinoctial elements is explained with a connection to orthogonal rotations and attitude dynamics in Euclidean 3-space. An identification is made between the equinoctial elements and classical Rodrigues parameters. A new set of equinoctial elements are then developed using the modified Rodrigues parameters.

03:30 PM **AAS 22-752: Orbital Acceleration Using Product of Exponentials**

Taylor Yow, Christopher Hays, Aryslan Malik and Troy Henderson*

The PoE formula for orbital mechanics is an alternate method for defining and drawing an orbit based on its orbital elements set, but unlike traditional methods, all six orbital elements are allowed to vary with respect to time. This work explores the second derivative of the adapted PoE formula for orbital mechanics, which gives a more complete description of the orbital motion of a satellite in a two-body system. This comprehensive approach employs a single equation to account for all six time-varying orbital element, therefore broadening the scope of orbital maneuvering research.

03:50 PM **AAS 22-827: Global Lunar Gravity Field Using Local Mascon Models**

Sean McArdle and Ryan Russell*

Weighted cubed-sphere mascon gravity models are introduced as runtime-efficient alternatives to the spherical harmonics representation that do not impose extreme memory costs. Localized models for the lunar gravity field are generated using sets of point-mass potentials and referenced to a cubed-sphere grid. Adjacent localized point mascon gravity models are combined using Junkins weighting functions to form a global model. Three demonstration models are generated that reproduce the GRGM1200A lunar gravity model with fidelity up to degree 550. The degree 550 model shows a 90-fold speedup in acceleration runtime compared to spherical harmonics with a 170 megabyte memory footprint.

04:10 PM **AAS 22-527: DYNAMIC MODELING OF SPACECRAFT WITH FLEXIBLE MEMBRANE**

Matthew Brownell, Puneet Singla and Andrew J. Sinclair*

The main focus of this work is to derive a mathematical model for a conceptual design of a large solar-powered spacecraft. The spacecraft is considered to be a flexible membrane clamped within a rigid, rectangular frame. The structure is motivated by a concept for capturing solar energy in space and accurately directing it to required locations on the Earth's surface. In subsequent work, we wish to utilize this model to develop data-driven modeling techniques to be used with real-time spacecraft input-output data.

Session: Orbit Determination and Space Surveillance Tracking III

Room: Carolina E, Time: 01:30 PM-04:30 PM

Session Chair: Christopher Roscoe (Ten One Aerospace)

01:30 PM

AAS 22-519: Uncertainty Propagation and Filtering via the Koopman Operator in Astrodynamics

Simone Servadio, William Parker and Richard Linares*

The Koopman Operator (KO) provides an analytical solution of dynamics systems in terms of orthogonal polynomials. This work exploits this representation to include the propagation of uncertainties, where the polynomials are modified to work with stochastic variables. Thus, a new uncertainty quantification technique is proposed, where the KO solution is expanded to include the prediction of central moments, up to an arbitrary order. The propagation of uncertainties is then expanded to develop a new filtering algorithm, where measurements are considered as additional observables in the KO mathematics. Numerical simulations in astrodynamics assess the accuracy and performance of the new methodologies.

01:50 PM

AAS 22-737: Optimal Nonlinear Particle Flow using Stein Variational Gradient Descent

Kyle Craft and Kyle DeMars*

In nonlinear Bayesian estimation, it is common to approximate the underlying probability distributions using a set of weighted particles. This process, known as particle filtering, is well documented to suffer from particle degradation, necessitating the resampling of particle weights. An alternative approach is to update, or flow, the particle locations within the state space without updating their weight. The particle flow presented herein utilizes Stein variational gradient descent (SVGD) to determine the optimal nonlinear update dynamics from which the particles "flow." A closed-form SVGD based particle flow algorithm is presented and applied to an orbit determination scenario.

02:10 PM

AAS 22-854: A Fourier series representation of satellite aerodynamic torques

Vishal Ray and Daniel Scheeres*

We develop a Fourier series expansion for the aerodynamic torques acting on a satellite using our previously developed Fourier models of the drag force for orbit determination. A framework is developed such that the torque Fourier coefficients can be estimated given measurements of the aerodynamic torque. Such a framework will allow a secondary source of measurement of atmospheric drag parameters without any additional payload. The pathway to combining this torque Fourier coefficients estimation scheme with orbit determination methods is laid out to provide accurate estimates of the atmospheric density and satellite drag coefficient.

02:30 PM

AAS 22-855: GEOMETRIC SOLUTION TO PROBABILISTIC ADMISSIBLE REGION (G-PAR) FOR SDA RADAR OBSERVATION

Utkarsh Mishra, Islam Hussein, Suman Chakravorty, Weston Faber, Benjamin Sunderland and Siamak Hesar*

Probabilistic Admissible Region (PAR) is a technique to initialize the pdf of a Resident Space Object(RSO) with guessed distributions of a few orbital elements and the observation. A geometrical solution to Probabilistic Admissible Region with Range, Range-rate observations is presented. The new formulation gives a closed-form solution for PAR particle mapping for the first time. It provides an easy-to-implement algorithm and clear geometrical reasoning for the resulting PAR pdf and explains why some samples fail to map into state space due to internal in- consistencies. G-PAR based pdf initiation in various orbital regimes is shown and numerical

02:50 PM

AAS 22-857: MULTIPLE OBJECT TRACKING WITH SDA RADAR OBSERVATIONS USING G-PAR FOR TRACK INITIATION

Utkarsh Mishra, Siamak Hesar, Benjamin Sunderland, Weston Faber, Suman Chakravorty and Islam Hussein*

A Geometrical solution to Probabilistic Admissible Region (G-PAR) is a method to initialize the pdf of the states of a Resident Space Object with a single partial observation and guessed distribution of a few states. For range, and range-rate measurements, G-PAR based track initiation and Particle Gaussian Mixture (PGM) based filtering is incorporated in a multi-target tracking filter called Random Finite Set Statistics (R-FISST II). The effectiveness of this troika (R-FISST II + G-PAR + PGM) is demonstrated in a multi-object tracking scenario with heavy clutter and variable probability of detection on the simulation side.

03:30 PM

AAS 22-689: Discrete State Estimation Using Bayesian Probability Theory

Christopher Roscoe, Michael Mercurio and Jason Westphal*

Estimation problems in astrodynamics typically involve systems with continuous states and are readily addressed by standard Bayesian filtering techniques. However, there are certain problems where the state and measurements can only take on a set of discrete values. For example, mission concepts have been presented to use lights blinking with unique patterns for satellite tracking or communication. Such concepts are predicated on observing a complete blink pattern, but noise may prevent a complete pattern from being observed. This paper addresses the problem of parameter estimation with discrete states and measurements, corrupted by clutter and missed detections, using Bayesian probability theory.

03:50 PM

AAS 22-622: Comparisons of Filtering Algorithms for Orbit Determination in Near Rectilinear Halo Orbits

Michael Thompson, Anthony Zara, Connor Ott, Matthew Bolliger, Ethan Kayser and Diane Davis*

As tools are developed for operational orbit determination and navigation in NRHOs for both Gateway and the upcoming CAPSTONE mission, there is interest in determining the potential limitations of commonly used tools and processes when applied to the unique dynamic regimes of the NRHO. This analysis seeks to provide direct comparisons between filtering methods for performing orbit determination in the 9:2 NRHO that will be utilized by Gateway and CAPSTONE. This analysis is divided into two broad categories: quantifying future uncertainty and current parameter estimation.

04:10 PM

AAS 22-735: Orbit Estimation of Resident Space Objects in Cislunar Space Using Satellite Sensor Formations

Ian Down, Davis Adams, James McElreath and Manoranjan Majji*

The use of a sensor satellite formation placed around a medium altitude, ’frozen’ lunar orbit to estimate the trajectories of resident space objects in cislunar space is studied in this paper. Statistical orbit estimation approaches are developed to assess the RSO observability as a function of the orbital regime, sensor system and formation characteristics. Vision-based and radio imaging sensor models are used, in conjunction with high-fidelity dynamical models to study the utility of the spacecraft formation in estimating the orbital characteristics of the RSO operating in cislunar space.

Session: Trajectory, Mission, and Maneuver Design and Optimization V

Room: Carolina A, Time: 01:30 PM-04:30 PM
Session Chair: Angela Bowes (NASA LaRC)

01:30 PM

AAS 22-549: Low-Thrust Transfer Design for the LISA Mission via the Libration Points SEL1 and SEL2
Anne Galda and Waldemar Martens*
The current transfer strategy of the LISA satellites to their heliocentric triangular cartwheel formation comprises a direct escape launch with fixed infinite velocity of 300 m/s. We present an alternative transfer design with a launch into the libration point regions 1 or 2 of the Sun- Earth system. The spacecraft energy at launch is optimised to maximise the spacecraft mass at arrival with initial guess obtained from the circular restricted three body problem. In this scenario, Earth's gravity provides the missing energy to enter the drift orbit, yielding an increase of up to 60 kg of spacecraft dry mass.

01:50 PM

AAS 22-594: Application of Tisserand's Criterion and the Lidov-Kozai Effect to STORM's Trajectory Design
Michael Shoemaker, David Folta and David Sibeck*
The Solar-Terrestrial Observer for the Response of the Magnetosphere (STORM) concept recently completed its Phase A design under NASA's Heliophysics Medium Explorers program. The mission design required a lunar gravity assist to insert into a 30-Earth-radii circular geocentric science orbit inclined 90 degrees to the ecliptic. STORM's trajectory design leveraged several interesting gravitational effects from third bodies. This paper describes our application of Tisserand's criterion for finding feasible transfers and lunar gravity assist trajectories, and the Lidov-Kozai effect to design a maneuver-free science orbit optimization and decommissioning strategy.

02:10 PM

AAS 22-601: An Optimized Trajectory for a Two-Stage, Surface to Orbit, Titan Launch Vehicle
*David Smith**
As part of a NIAC funded Titan sample return mission, NASA GRC's Compass Team has investigated a two-stage, in-situ propellant, launch vehicle design. This paper presents a proposed trajectory for the vehicle and mission of interest. This trajectory is optimally solved to balance drag losses in the denser atmosphere along with gravity losses accumulated during vehicle ascent to select an optimal path from Titan's surface to a orbit insertion. The resulting trajectory is characterized by a slow, vertical climb to an altitude above the densest part of the atmosphere followed by a pitch-over and climb to orbital insertion. The resulting ΔV is 3.96 km/s.

02:30 PM

AAS 22-550: Titan Sample Return Mission using V-Infinity Leveraging
Jeffrey Pekosh and Steven McCarty*
The unique environment of the Saturnian moon Titan provides a particular incentive for a sample return mission. The thick atmosphere and low gravity provide both useful benefits and harrowing challenges that make optimizing any return trajectory especially important in order to maximize return. V-Infinity leveraging provides a unique capability for finding lower delta-v return trajectories which can be reliably converged from theoretical results, regardless of the departure epoch. This paper will demonstrate the ability to use this technique to enable Titan sample missions and examine it relative to other options.

02:50 PM **AAS 22-816: Mission Design for the Sherpa GEO Pathfinder**

Lisa Policastri, Marissa Intelisano, Mike Loucks and Stephen West*

The GEO Pathfinder, which will launch as a rideshare with the IM-2 lunar lander, is a Spaceflight Inc. Sherpa-ES spacecraft which will place payloads in a geostationary orbit via a lunar flyby. The Sherpa-ES will divert from the IM-2 lunar trajectory and use a lunar flyby to target a return to the Earth at a low inclination. The Sherpa-ES will then use its bipropellant propulsion system to perform a series of apogee-reduction maneuvers to circularize in geostationary orbit. This paper summarizes the trajectory design tradeoffs, analysis of the launch periods, and the orbit determination approach.

03:30 PM **AAS 22-839: Near-Term Strategies to Rendezvous with an Interstellar Object**

Damon Landau, Benjaman Donitz and Reza Karimi*

Interstellar Objects (ISOs) provide a unique opportunity to investigate comets and asteroids that originate outside our solar system. While fast flyby missions are currently feasible, rendezvous missions that orbit or even land would provide literal ground truth into these new targets. Mission design and propulsion capability are current challenges due to the brevity of ISO paths through the Solar System. These challenges may be overcome with a trade space exploration of detection capabilities, launch vehicles, trajectory designs, and near-term spacecraft technology development. The combination of Jupiter flyby and nuclear electric propulsion improves the likelihood of rendezvous with a new ISO.

03:50 PM **AAS 22-833: Preliminary Trajectory Design Method for Continuous Thrust Synergetic Maneuvers for Planetary Flybys**

Ghanghoon Paik and Robert Melton*

A solution to Lambert's problem gives the required delta-v to transfer from one point to another in a given time of flight. The porkchop plot is a set of Lambert's solutions (delta-v's) within a given range of dates which provides windows of launch or arrival dates. A series of Lambert's solutions can be used to generate a sequence for multiple planetary visits. In addition to continuous thrust during the flyby phase, layers of porkchop plots can be combined for path planning. This paper introduces an idea to design a gravity assist mission trajectory with applied continuous thrust synergetic maneuvers at the planetary encounters.

Session: Spacecraft Guidance, Navigation, and Control II

Room: Carolina C, Time: 01:30 PM-04:30 PM

Session Chair: Jason Leonard (KinetX)

01:30 PM

AAS 22-774: Higher-Order Feedback Control Law For Low-Thrust Spacecraft Guidance

Taehyeun Kim, Spencer Boone and Jay McMahon*

In this work, we will derive a higher-order feedback law for a continuous-thrust spacecraft trajectory, with the objective of expanding the convergence region of the guidance law when compared to a linear method. Differential dynamic programming (DDP) is used with higher-order STTs to construct the feedback control law. We will compare the performance of the higher-order feedback law with the linearized method for low-thrust trajectories in several highly nonlinear dynamic systems, such as the Earth-Moon system.

01:50 PM

AAS 22-553: Rapid Finite Fourier Series Approximations of Sub-Optimal Low-Thrust Space Trajectories

Benjamin Schimke and Ossama Abdelkhalik*

Fast design methods for low-thrust trajectories prove useful when performing space mission optimization. Typical trajectories of this type involve slowly developing spirals around planetary bodies; one such method to generate these paths utilizes a finite Fourier series (FFS) approach, where the system's state is approximated using an expansion of coefficients. The presented work extends this FFS method by leveraging costate approximations to satisfy the necessary conditions for optimality at discrete points. The process aims to function as an intermediate step between the traditional FFS and higher fidelity solvers, achieving initial guess generation closer to the optimal solution.

02:10 PM

AAS 22-582: Stationkeeping of Periodic Orbits Using High-order Target Phase Approach

Xiaoyu Fu, Nicola Baresi and Roberto Armellin*

To maintain the periodic orbits in a three-body regime, a high-order Target Phase Approach (TPhA) is proposed in this work. Two crucial maps, the phase-angle Poincare map and high-order maneuver map are established respectively for the determination of stationkeeping epochs and calculation of of correction maneuvers. A stochastic optimization framework tailored for the TPhA-based stationkeeping process is leveraged in search of the fuel-optimal and error-robust TPhA parameters. Quasi-Satellite orbits around the Phobos are investigated to demonstrate the validity and efficiency of this approach in both low- and high-fidelity models. Primer vector theory is employed to explore the optimality of TPhA maneuvers.

02:30 PM

AAS 22-844: Sequential linearization-based station keeping with optical navigation for NRHO

Purnanand Elango, Stefano Di Cairano, Karl Berntorp and Avishai Weiss*

In recent years, fuel-efficient station-keeping techniques have been developed for the planned Lunar Gateway mission to a near rectilinear halo orbit (NRHO). Station-keeping approaches that rely on an autonomous navigation system which doesn't require communications with Earth are particularly important for ensuring safety and reliability. This paper presents a targeting approach for NRHO station keeping based on sequential linearization and evaluates its performance in a closed-loop simulation with a state estimator that receives position measurements from horizon-based optical navigation (OpNav). Simulation results indicate an annual station-keeping cost (delta-v) of about 1 m/s for the proposed OpNav-based station keeping.

02:50 PM **AAS 22-805: Near-Optimal Waypoint Selection for Enforcing Trajectory Constraints**

Zachary Rhodes and Brian Kaplinger*

For spacecraft rendezvousing, guidance algorithms like Zero-Effort-Miss/Zero-Effort-Velocity (ZEM/ZEV) may be used. In this document, a process for selecting near-optimal waypoints to enforce path constraints using closed-loop guidance algorithms is presented. This research proposes to use a genetic algorithm to select a waypoint minimizing resources as defined by the objective function. Waypoint selection is successive over fixed intervals until the target is reached. Breaking the trajectory into sections decreases the usage of limited resources onboard. The performance of the waypoint selection and its relationship to trajectory cost are discussed. This paper discusses the trajectory selected and commanded acceleration output from the ZEM/ZEV guidance.

03:30 PM **AAS 22-678: End-to-End Mars Aerocapture Analysis Using Linear Covariance Techniques and Robust Trajectory Optimization**

Jack Joshi, Zachary Putnam and David Woffinden*

Previously, Monte Carlo simulation techniques have been used to perform uncertainty analysis supporting aerocapture at Mars. In this analysis, linear covariance techniques are leveraged to provide an accurate analysis alternative for an aerocapture mission at Mars, with a focus on mission design and integrated guidance, navigation, and control performance. Preliminary results show that a numeric predictor-corrector guidance algorithm allows the vehicle to target a desired apoapsis at a minimal delta-v cost. Additionally, trajectory correction maneuvers and Deep Space Network updates will be optimized such that the dispersions and navigation errors at atmospheric interface and in the final target orbit are minimized.

03:50 PM **AAS 22-740: Constrained Reachability Analysis for Mars Planetary Landing with Aerodynamic Forces via Convex Optimization**

Kazuya Echigo, Daniel Dueri and Behçet Açıkmeşe*

This paper proposes a method to compute convex over-approximations of the reachable sets for the Mars-powered descent and landing problems with all the relevant constraints. The proposed algorithm is based on piecewise linearization of the nonlinear dynamics, where the linearization error is bounded accurately via polytopes by applying interval analysis-based methods. At each discrete time step, a reachability subproblem is solved. Since the dynamics are linearized and all constraints are convex, a previously developed convex optimization-based method is then used to efficiently compute a tight over-approximation of the reachable set of the actual nonlinear system to arbitrary accuracy.

04:10 PM **AAS 22-670: Efficient Nonlinear Spacecraft Navigation Using Directional State Transition Tensors**

Oliver Boodram, Spencer Boone and Jay McMahon*

To capture nonlinear dynamical effects, filters implement state transition tensors (STTs), higher order expansions of the solution flow, to propagate spacecraft states forward in time. Unfortunately, numerical implementation of STTs can be expensive. In this work, we implement directional state transition tensors (DSTTs), solution flow differentiated along a rotated basis, into the higher-order Extended Kalman Filter to approximate the number of terms required for propagation while maintaining accuracy. This approximated filter is applied to non-linear dynamical environments such as a near-rectilinear halo orbit (NRHO) in the Earth-Moon circular restricted three-body problem, and its performance is compared against alternative filters.

Thursday, August 11

Session: Spacecraft Guidance, Navigation, and Control III

Room: Carolina D, Time: 08:00 AM-12:00 PM

Session Chair: Sergei I. Tanygin (Vast, LLC)

08:00 AM **AAS 22-547: Identification of Mass, Stiffness, and Damping Matrices For Structural Models with Rigid Body Modes**

Dong-Huei Tseng, Minh Phan, Richard Longman and Raimondo Betti*

This paper presents a method to identify the mass, stiffness, and damping matrices of structural models with rigid body modes from force inputs to acceleration outputs. The full-order state-space models of such structures are unobservable, thus existing state-space based methods cannot be directly applied. The developed method converts the full-order models with symmetric mass, stiffness, and damping matrices to reduced-order models with non-symmetric stiffness and damping matrices, identifies the reduced-order models, then recovers the original full-order model symmetric mass, stiffness, and damping matrices. Both simulation and experimental results are presented to validate the proposed method.

08:20 AM **AAS 22-608: Venus Atmospheric Probe and Flyby Relay Spacecraft Cross-Link Tracking Impact on Relative Pointing Accuracy**

Bobby G. Williams, Jason Leonard, Jeremy Knittel, Kenneth Williams, Jim McAdams and Sun Hur-Diaz*

Scientific exploration of Venus using an atmospheric probe requires relaying telemetry to Earth as the probe descends through the atmosphere to the surface of Venus. Using the flyby spacecraft to relay the probe telemetry to Earth will require precise carrier-to-probe pointing accuracy of the relay spacecraft's antenna. NASA's Deep Atmosphere Venus Investigation of Noble gases, Chemistry, and Imaging (DAVINCI) mission uses this carrier-to-probe relay technique. Although DAVINCI includes a coherent cross-link for science, this is not baselined for navigation tracking. This paper explores the potential effectiveness of cross-link tracking for reducing trajectory uncertainty and improving spacecraft-to-probe pointing.

08:40 AM **AAS 22-596: Attitude Dynamics of On-orbit Refueling Configurations**

Jing Pei and Carlos Roithmayr*

On-orbit refueling is a key enabling technology that will allow a significant increase in the amount of payload mass delivered beyond low-Earth orbit. Despite the potential benefits, there are numerous concerns regarding the operability and scalability of this critical technology. This paper explores the attitude dynamics of two docked spacecraft performing propellant transfer. A vector equation is derived to account for the change over time in the mass distribution and the position of the mass center of the stack.

09:00 AM **AAS 22-761: Minimal Mass Column Theory: A Tensegrity Prism Approach**

David Capps and Manoranjan Majji*

Novel tensegrity prism column topologies and their structural mechanics characterization is presented in the paper, building upon prior work on tensegrity prisms. Traditional class 1 and class 2 solutions to the tensegrity system p-bar prism column problem are analyzed and their minimal masses for an applied force are determined. Insightful analysis is carried out to determine stiffness optimization criteria for minimal mass. Based on the analytical developments, new column topologies are introduced. The dual prism and non-minimal prism are developed and compared to the traditional topologies to explore different options for the tensegrity column. These are also compared to other

09:20 AM **AAS 22-536: Minimum-Time Reorientation of Axisymmetric Rigid Spacecraft Using the BBSOC Method**

Elisha Pager and Anil Rao*

A minimum-time reorientation of an axisymmetric rigid spacecraft controlled by three torques is studied. The orientation of the body is modeled such that the attitude kinematics are representative of a spin-stabilized spacecraft. The optimal control problem considered is shown to have a switching control structure. Moreover, under certain assumptions, the solutions contain segments that lie on a singular arc. A numerical optimization study is performed using a recently developed method, the BBSOC method, that is designed to accurately solve bang-bang and singular optimal control problems.

09:40 AM **AAS 22-810: Trajectory-Planning Attitude Control System for Satellites with Magnetic Attitude Control and One Reaction Wheel**

Patrick McKeen, Alex Meredith and Kerri Cahoy*

We consider an attitude control system for LEO spacecraft that relies on a single reaction wheel and three magnetorquers (1RW+3MTQ), resulting in lower size, weight, power, and cost (SWaP-C) than state-of-the-art systems, which typically require three reaction wheels and additional actuators for desaturation. We use a trajectory planning control method that prioritizes meeting pointing goals while minimizing the need to desaturate the reaction wheel. Planning ahead allows for time-changing goals and the use of control throughout a trajectory to improve performance during a specific subinterval. Preliminary results show pointing performance similar to a system with three reaction wheels. We consider

10:20 AM **AAS 22-617: A PRACTICAL INTERPOLATING PRE-FILTER FOR CLOSED-LOOP ATTITUDE GUIDANCE**

Mark Karpenko, Joshua Levitas and Roberto Cristi*

Attitude guidance is a concept for implementing performance enhancing rotational maneuvers that uses a conventional closed-loop attitude control system to track a maneuver trajectory. Minimum-time attitude guidance is presently being used for executing fast occultation avoidance maneuvers on NASA’s Lunar Reconnaissance Orbiter (LRO). A challenge in operationalizing the idea is related to the limited size of the spacecraft's command buffer, which was not designed with maneuver tracking in mind. In this paper, we propose an interpolating pre-filter built on B-splines that can be used to process downsampled manuever commands (to save buffer space) to provide controller inputs at the servo-rate.

10:40 AM **AAS 22-568: Unscented Kalman Filter using Modified Spherical Coordinates for Passive Spacecraft Angles-Only Relative Navigation**

Matthew Givens and Jay McMahon*

Autonomous navigation relative to a target spacecraft using only angle measurements, such as those provided by onboard camera sensors, is a challenging problem that has been the subject of many past analyses. Here, we re-propose the use of Modified Spherical Coordinates (MSCs) as a reliable state parameterization to properly capture the uncertainty associated with angular measurements. We show a straightforward application of MSCs in an Unscented Kalman Filter (UKF) makes for a consistent sequential filtering solution with low computational requirements and contrast it to other comparable algorithms.

11:00 AM **AAS 22-790: Generalized Formalism for Variable-Mass-Property Spacecraft Dynamics Utilizing Rigid Body Motion on Lie Groups**

Brennan McCann, Herman Gunter, Morad Nazari and Troy Henderson*

For rigid-body spacecraft, rotational and translational motions are often coupled and their treatment in an appropriate dynamical framework is important. Forming the problem on the special Euclidean group (SE(3)) treats this coupling and does not fall victim to singularity and nonuniqueness issues. Presented herein is an approach to treating variable-mass-property spacecraft as a collection of discrete rigid bodies on SE(3). The method proposed is applied to the cases of a dual spin spacecraft and a variable-center-of-mass rigid body and is shown to generalize Tsiolkovsky's rocket equation to rigid-body spacecraft.

11:20 AM **AAS 22-651: Modelling of Propellant Slosh Dynamics and its Application in Control Stability Study of Lunar Landing Mission**

Nivriti Priyadarshini, Debajyoti Chakrabarti and Yajur Kumar*

Propellant sloshing during liquid-engine burn operation of a spacecraft interacts with its dynamics and influences overall stability of the spacecraft. In this paper a high-fidelity slosh dynamics model is developed based on analogous mechanical(pendulum) model and applied to emulate the sloshing phenomena observed during initial phase of powered-descent mode in *Chandrayaan-2* lunar landing mission. The center-of-percussion study augmented by stability analysis based on the proposed slosh model, followed by rate-sensitivity study, clearly reproduces the zone of predominant slosh behavior during the mission. A close comparison of six degree-of-freedom simulation results with on-board observed rate further establishes the slosh dynamics model.

11:40 AM **AAS 22-628: Attitude control for flight phase of quadruped robots in low-gravity environment using reaction wheels and swing legs**

Chunyang Zhou, Keying Yang, Jingrui Zhang and Quan Hu*

Attitude stability is a prerequisite for the motion control. In this study, the attitude control issue for the flight phase is investigated. The attitude of the robot is controlled by a set of three reaction wheels embedded in the torso, as well as the swing motion of the legs. An active disturbance rejection controller is developed to achieve the attitude stabilization of the system in flight phase. Then, a steering law is designed to obtain the hybrid command for the reaction wheels and swinging legs. Numerical examples demonstrate the efficacy of the proposed method.

Session: Orbital Debris and Space Environment

Room: Carolina E, Time: 08:00 AM-12:00 PM
Session Chair: Brian Gunter (Georgia Institute of Technology)

08:00 AM

AAS 22-542: Deriving Event Thresholds and Collision Probability for Automated Conjunction Assessment at Mars and the Moon
Zahi Tarzi, David Berry and Brian Young*
There is an increasing number of missions to Mars and the Moon and an inability to track debris in these environments, necessitating conjunction assessment analysis to prevent spacecraft collisions and reduce orbital debris. The Multimission Automated Deepspace Collision Avoidance Process (MADCAP) is used at the Jet Propulsion Laboratory to perform conjunction assessment at Mars, the Moon, and Sun/Earth libration points. Previous papers have described this process and its development. This paper will explore the development of the conjunction event thresholds used in MADCAP and provide guidance for navigation teams to derive them. Collision probability calculations are also examined.

08:20 AM

AAS 22-571: Comparison of Gaussian processes and Neural Networks for thermospheric density predictions during quiet time and geomagnetic storms
Wang Yiran and Xiaoli Bai*
In this paper, we develop a machine learning (ML) based, data-driven density prediction framework that integrates satellite accelerometer data, solar and geomagnetic indices, and empirical models including NRLMSISE and JB. Two types of ML methods are explored and tested during geomagnetic quiet time and storm scenarios. The first ML method is a heteroscedastic and sparse Gaussian Processes model. The second ML method is based on Neural Network and the Monte Carlo dropout method is used to provide a measure of uncertainty. Preliminary studies have led to insightful temporary conclusions. For the full paper, comprehensive studies and analyzes will be conducted.

08:40 AM

AAS 22-757: A New Analytical Method for Eclipse Entry/Exit Positions Determination Considering a Conical Shadow and an Oblate Earth Surface
Marco Nugnes and Camilla Colombo*
Satellite eclipse determination is one of the most important tasks to be analyzed in the preliminary design of a planetary space mission. Indeed, the duration of the eclipse is a driver for the sizing of the batteries that must be used when solar energy is not available. This paper wants to define a new analytical procedure for the determination of the entry/exit anomalies of a satellite inside a conical shadow generated by the Earth surface modelled as an oblate ellipsoid of rotation. The methodology is tested for different orbit scenarios and is compared with state-of-the art algorithms.

09:00 AM

AAS 22-819: Accuracy of Density and Accommodation Coefficient Estimates as a Function of Drag Force and Torque Errors for a Paddlewheel CubeSat
Wyatt Webb and Craig McLaughlin*
The inaccuracy in current atmospheric density models is a leading factor towards the difficulty in estimating lifetime and predicting trajectories for LEO satellites. The goal is to use a 3U paddlewheel CubeSat designed to generate sufficient drag force and torque to allow estimation of density and accommodation coefficient in LEO. To determine the accuracy needed for drag and force measurements a data simulation was developed. This simulation allows for simultaneous solving for density and accommodation coefficient throughout the simulated orbit based on the given inaccuracy for drag force and torque measurements.

09:20 AM **AAS 22-849: Quantifying the Effect of Uncertainty in the Brightness Measurements of a Lightcuve on the Shape Inversion Diversity**
*Carolin Frueh**
Brightness measurements over time, so-called light curves contain information about a space object's shape, attitude, and materials for a given observation geometry. Measured real light curves are subject to noise. As a result, the shape inversion process allows, within those uncertainties for a variety of shapes. This paper derives a measure via the in- and out radius of convex polygons to quantify differences in shapes recovered from light curves.

09:40 AM **AAS 22-798: Orbital Drag Near Small Bodies Due to Lofted Fines from Surface Activity**
Matthew Wittal and Dan Batcheldor*
Small bodies have been shown to be more granular and dusty than previously expected. Furthermore, as a result of landings, mining, or natural impacts, bodies with negligible atmospheres, such as moons and asteroids, may experience an exospheric environment abundant in lofted fines. Significant quantities of these may interfere with the nominal trajectories of spacecraft in low orbits. This work investigates the threshold of activity that would induce concerns about a spacecraft's nominal mission around various bodies including the Moon, Bennu, Comet Wild-2, and Phobos. Coupled motion of spacecraft navigation and control is expressed in SE(3)

10:20 AM **AAS 22-661: Design and Analysis for Experimental Validation of Touchless Charge Control Testing**
James Walker, Julian Hammerl and Hanspeter Schaub*
Remote sensing of spacecraft potentials is necessary to reduce risks during docking and proximity operations between two spacecraft. Current methods utilize an electron beam impacting the surface of a target to measure charge. This inflow of electrons will alter the potential of the target. Proposed methods of charge control could be used to mitigate this effect, however testing requires the target to be held at a constant potential. Adding a large capacitor and a high voltage power supply in series with the target will generate a drain current, more accurately simulating spacecraft charging. This will allow for experimental validation of proposed charged control techniques.

10:40 AM **AAS 22-655: Preliminary Debris Risk Assessment for Mega-Constellations in Low and Medium Earth Orbit Due to Satellite Breakup**
Joseph Canoy and Robert Bettinger*
The theoretical analysis of low Earth orbit mega-constellations and the potential risk due to artificiar debris clouds found in LEO is presented. The mega-constellations will be modeled off of Starlink and OneWeb, which will include approximately 750 satellites. These satellites will be positioned using Walker-Delta design. The Monte Carlo simulation will have debris originating from the single breakup of a randomly selected satellite per simulation. Cascading debris events will not be modeled in this research. Based on theresults of simulations, debris risk calculation of probability of calastrophic collision is found and compared with a theoretical mega-constellation in medium Earth orbit.

Session: Trajectory, Mission, and Maneuver Design and Optimization VI

Room: Carolina A, Time: 08:00 AM-12:00 PM

Session Chair: Rohan Sood (The University of Alabama)

08:00 AM

AAS 22-679: Designing Multiple Missed Thrust Event Resilient Trajectories using Virtual Swarms

Ari Rubinsztejn, Rohan Sood and Frank Laipert*

Low-thrust propulsion is an enabling factor for the next generation of deep-space missions. Unfortunately, their limited thrust capabilities render long-duration thrusting arcs necessary and make the spacecraft susceptible to multiple missed thrust events. This investigation extends the virtual swam approach for designing missed thrust resilient trajectories to the multiple missed thrust event scenario. The proposed methodology is successfully able to generate missed thrust resilient trajectories and provides evidence that the terminal coast approach is closer to an optimal method than previously known.

08:20 AM

AAS 22-784: Robust Spacecraft Maneuver Design with Non-Gaussian Chance Constraints Using Gaussian Mixtures

Spencer Boone and Jay McMahon*

Many existing chance constraint maneuver design formulations rely on the assumption that the state uncertainties can be approximated as Gaussian distributions. For many astrodynamics scenarios, this assumption does not hold since the uncertainties are decidedly non-Gaussian. In this work, we use Gaussian mixture models to approximate non-Gaussian chance constraints. We then apply iterative risk allocation to optimally allocate risk between the different mixands in the mixture. We apply the control scheme to several spacecraft maneuver targeting applications with non-Gaussian state distributions. Results show that the method produces maneuvers which accurately meet the desired probabilistic constraints.

08:40 AM

AAS 22-600: State Perturbation Tradespaces in Trajectory Targeting Convergence Analysis

Collin York, Kathleen C. Howell and Belinda Marchand*

One robustness measure in trajectory targeting is the ability to determine feasible trajectories under state perturbations. In targeting problems, a tradespace is available between individual position and velocity perturbations, and a Pareto frontier emerges that yields similar convergence behavior. Characterization of the convergence basin and resulting Pareto frontier is explored in the Circular Restricted Three-Body Problem via discretized approaches and a basin metric produced from 1st- and 2nd-order state transition tensors evaluated on the reference path. The correlation between these approximations and the criteria to assess the applicability of such models are summarized.

09:00 AM

AAS 22-613: An hp Mesh Refinement Method using Density Functions for Hypersensitive Optimal Control

Gabriela Abadia and Anil Rao*

Hypersensitive optimal control problems are characterized by a long equilibrium segment that is preceded and followed by initial and terminal boundary-layer segments, respectively, corresponding to the contraction and expansion of the Hamiltonian dynamics in the neighborhood of the optimal solution. The stable and unstable behaviors can be decoupled using a dichotomic basis for the tangent space. The research in this paper proposes using Legendre-Gauss-Radau collocation along with the rate coordinate decomposition of the system that results from the dichotomic basis method in order to generate density functions for hp mesh refinement.

09:20 AM **AAS 22-621: Semi-Analytical Optimal Orbit Raising Using Hill's Equations**

Aimar Negrete and Ossama Abdelkhalik*

The orbit raising problem is formulated as a maximum energy transfer and solved in a semi-analytic fashion for a spacecraft with constant thrust acceleration magnitude. Instead of using the nonlinear dynamics of the relative two body problem, the linear Hill-Clohessy-Wiltshire (HCW) equations of motion are used as an approximation for the dynamics. Using indirect methods, the optimal control law for this problem is derived analytically in terms of the states at the final time, and an iterative method is used to approximate the final states. A recursive method is proposed to generate full orbit raising trajectories.

09:40 AM **AAS 22-631: Fundamental attitude dynamic characteristics of solar sails in low-Earth orbit with active control**

Maximilien Berthet and Kojiro Suzuki*

The thrust generated by solar sails is modulated by their attitude. Detailed knowledge of the pointing error is needed to ensure adequate orbital performance. This is especially true in LEO, where solar sails experience multiple, time-changing, severe attitude disturbances. Traditional coupled orbit-attitude simulation is not adapted to this problem setting due to the variety and complexity of contributing physical effects. This study develops a general pointing error model for solar sails with active attitude control, using simple physical assumptions and directional statistics. The results show good agreement with experimental flight data and predictions from a high-fidelity coupled orbit-attitude simulator.

10:20 AM **AAS 22-619: MINIMUM-TIME MANEUVERS OF THE JAMES WEBB SPACE TELESCOPE**

Timothy Polyard and Mark Karpenko*

Flagship observatories like the James Webb Space Telescope (JWST) are expensive to build and costly to operate. Not surprisingly, the more time that is spent acquiring science the greater the return on investment (ROI) since the system cost is amortized over science observations. Slewing the observatory from target to target reduces the time on science and so improving slewing efficiency can therefore increase the system ROI. In this paper, we develop and analyze minimum-time maneuvers for JWST that accommodate attitude constraints associated with the sunshield as well as practical reaction wheel torque and momentum limits.

10:40 AM **AAS 22-776: Three Years of On-Orbit Angular Momentum Management for the Parker Solar Probe Mission**

Kevin Liu and John H. Wirzburger*

Parker Solar Probe (PSP) is a mission to “touch” the Sun and unravel the mysteries of the Sun’s corona and solar wind. PSP has ventured into a uniquely intense solar environment where solar radiation pressure applies a significant external torque on the spacecraft, which has impacts on mission operations. In this paper, we describe how the Guidance and Control team modeled solar torque and implemented a strategy of passive momentum management. Then, we describe three specific on-orbit situations that caused angular momentum to behave differently from the majority of the mission, and how their effects were modeled.

11:00 AM **AAS 22-699: Optimal Lunar Transfer for CubeSat with Electrospray Propulsion**

Ivan Martinez I Cano and Kenneth Mease*

Motivated by a proposed mission to construct, from multiple CubeSats, a large aperture radio telescope behind the Moon to detect emissions from exoplanets, efficient Earth to Moon transfer options are identified and compared. Each CubeSat has an electrospray propulsion (ESP) system that operates at constant input power while allowing a continuous range of specific impulse and thrust combinations. Using the circular restricted 3-body model augmented for the ESP thrust, minimum time and minimum propellant transfers are computed. The transfer options considered all involve arcs on stable and unstable manifolds of unstable periodic orbits to reduce propellant consumption.

Session: Relative Motion and Formation Flying IV

Room: Carolina C, Time: 08:00 AM-12:00 PM
Session Chair: Davide Guzzetti (Auburn University)

08:00 AM **AAS 22-653: Rapid Discrete Planning for Satellite Constellation Imaging Missions**

Greg Droge, Konnor Andrews and James Swedeen*

This paper develops and evaluates three rapid planning techniques used to schedule satellites for earth imaging missions. Previous results suggest that the optimal solution produced by a Mixed Integer Linear Programing (MILP) solver is very similar to a longest path, even though the constraints disallow the longest path solution. Thus, a greedy modification to a longest path search is developed. The second planner developed is based upon ant colony optimization techniques to allow random walks for improving solutions. The final technique developed is the utilization of these greedy planners as a hot start for MILP optimization.

08:20 AM **AAS 22-654: A Two-Layer Constellation Scheduling Approach for Imaging and Communication**

Greg Droge, Skylar Cox, Justin Whitaker and John Humble*

This paper develops a constellation scheduling capability for an earth imaging mission. Considering various spatial and temporal constraints, a two-layer planner is used to schedule collection, crosslink images between satellites, and scheduling of the ground-link terminal. The first level creates a communication plan for downlink and crosslink tasks using heuristics to calculate the opportunity costs for communicating instead of imaging. The communication plan is then passed to a POI collection planner, which schedules imagery collection between existing communication time windows. A network flow approach is used at each level to formulate and solve the problem using mixed integer linear programming.

08:40 AM **AAS 22-744: Application of Markov Decision Processes to Spacecraft Formation Shape Control**

Michael Mercurio, Christopher Roscoe and Jason Westphal*

Spacecraft formations have been identified as a key enabler in meeting increasingly complex mission requirements. Formations are selected to meet specific mission goals such as synthetic aperture sizing and ground target revisit rate, and may be varied throughout the mission. Management and configuration of formations often involves centralized processes to coordinate maneuvers among multiple spacecraft, prohibiting extension to on-orbit decision making. This paper addresses the formation shape reconfiguration problem through application of Markov Decision Processes, a framework for decision making under uncertainty.

09:00 AM **AAS 22-778: Coevolving Defender Strategies within Adversarial Ground Station Transit Time Games via Competitive Coevolution**

Manuel Indaco, Sean Harris, Deacon Seals, Daniel R. Tauritz, Samuel Mulder and Davide Guzzetti*

While daily activities are facilitated by the services provided by emerging P-LEO constellations, the increasing number of satellites constitutes a wide attack surface for malevolent actors. If such an event were to happen, a prompt reaction is necessary to reduce the consequences of the attack. In this work, we employ competitive coevolution to solve an adversarial ground station transit time game: while an attacker evolves smart locations to degrade the performance of a constellation, a defender evolves a strategy to counter the attacker's action. The effectiveness of the method is assessed via several tests and comparison with a hand-crafted solution.

09:20 AM

AAS 22-812: Modeling and Gamification Framework of Business Competition Between P-LEO Constellations

Rehman Qureshi, Cody Roberts, Manuel Indaco, Emily Kimbrell, Lucy Bone, Samuel Mulder, Daniel R. Tauritz and Davide Guzzetti*

We present an approach for developing a gamified framework in which multiple players develop and operate their own mega-constellations. Using a mixture of gamification and modeling, the framework simulates business competition between constellation operators offering satellite internet services to virtual customers. Individual zero-order models are incorporated together to create a real-time-strategy game. This framework is designed to model competition in the satellite internet marketplace and subsequent domain of potential business strategies (otherwise known as policies). Future work will utilize human players and AI agents to search the policy space. The goal is to identify equilibrium conditions and novel business strategies.

09:40 AM

AAS 22-825: Maximizing Observation Throughput via Multi-Stage Satellite Constellation Reconfiguration

Hang Woon Lee, Hao Chen and Koki Ho*

We examine the problem of multi-stage satellite constellation reconfiguration in the domain of Earth observations. The goal of the problem is to maximize the total system observation throughput by directly manipulating the orbits of the constituent satellites. We propose a novel integer linear programming formulation of the problem that is constructed based on the concept of time-expanded graphs. An illustrative example is presented to demonstrate the value of the proposed framework.

10:20 AM

AAS 22-707: Feasibility Studies for an Autonomous Cislunar Position, Navigation and Timing Constellation

Dhathri Harsha Somavarapu, Davide Guzzetti and Siamak Hesar*

Currently in literature, knowledge about orbit and constellation configurations for provisioning a position, navigation and timing (PNT) service in cislunar space is limited. This work contributes to advancing the understating of the design space for PNT constellations servicing the cislunar space. We conducted feasibility studies to identify a potential orbit configuration and constellation configuration for providing coverage in the cislunar region with the spacecraft that serve as the observers in the PNT constellation. The ultimate goal of this PNT constellation is to facilitate autonomy for the cislunar space faring missions and increase mission and science throughput.

10:40 AM

AAS 22-556: LISA Point-Ahead Angle Control for Optimal Tilt-to-Length Noise Estimation

Niklas Houba, Simon Delchambre, Tobias Ziegler, Gerald Hechenblaikner and Walter Fichter*

The Laser Interferometer Space Antenna (LISA) mission features a three-spacecraft longarm constellation intended to detect gravitational-wave sources in the low-frequency band via laser interferometry. The paper presents an open-loop control strategy for point-ahead angle (PAA) correction required to maintain the optical links of the moving constellation. The control strategy maximizes periods between adjustments on constellation level and is shown to be optimal from the perspective of estimating and correcting tilt-to-length (TTL) coupling. TTL is a noise source that couples angular spacecraft jitter to longitudinal interferometer measurements. Without precise TTL noise estimation and correction, it fundamentally limits the detector's sensitivity.

11:00 AM **AAS 22-580: CLING-ERS: Optimizing RPO Ease for Assembly Operations**

David Barnhart, Adarsh Rajguru, Jonathan Nguyen and James Lee*

Ubiquitous, low cost, autonomous and safe docking may well open up a Trillion-dollar market in on-orbit assembly and infrastructure build in space. USC's Space Engineering Research Center (SERC) has developed **CLING-ERS,** a single simple connecting device that merges mechanical connectivity with embedded rendezvous sensors. CLING-ERS objective is to offer a low cost commercially acceptable standalone autonomous navigation and connecting system for any space object to enable servicing and assembly operations from small to large size objects.

11:20 AM **AAS 22-850: Design Considerations for Attitude Consensus Control of Two Flexible Spacecraft**

Laqshya Taneja and Eric Butcher*

A numerical study of a Morse-Lyapunov-based relative attitude and relative angular velocity controller is conducted on two flexible spacecraft flying in formation. Response surface maps across a sweep of control parameters reveal that operating in a less aggressive regime (high velocity gain and low attitude gain) beneficially reduces both control effort and settling time for a nominal relative attitude offset. Meanwhile, a trade-off between both objectives must be considered for an off-nominal set of initial conditions. Furthermore, it appears that increased rigid-flexible coupling provides undesirable feed-through of flexible vibrations that must be managed using additional control expenditure.

11:40 AM **AAS 22-703: Robust Adaptive Control via Nonsingular Terminal Sliding Mode for a Virtual Telescope**

Soobin Jeon, Hancheol Cho and Sang-Young Park*

A continuous adaptive controller is developed for orbit and attitude control in the presence of structural uncertainties and external disturbances for a virtual telescope mission. A continuous control law is designed based on the sliding mode control theory so that it can avoid chattering and guarantees finite-time convergence into a small domain with initial errors. A simple adaptive law autonomously adjusts the control gain without knowing the uncertainties. The hyperplane-based nonsingular terminal sliding variable ensures a fast convergence rate while retaining robustness. The proposed adaptive control strategy is applied to the inertial alignment mission to show its robustness and accuracy.

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