31ST AAS/AIAA SPACE FLIGHT MECHANICS MEETING
CONFERENCE INFORMATION

GENERAL INFORMATION

Welcome to the 31st Space Flight Mechanics Meeting, hosted by the American Astronautical Society (AAS) and co-hosted by the American Institute of Aeronautics and Astronautics (AIAA), February 1 – 3, 2021. This meeting is organized by the AAS Space Flight Mechanics Committee and the AIAA Astrodynamics Technical Committee, and held virtually due to the ongoing COVID-19 pandemic.

REGISTRATION

Registration Site (** *https://www.xcdsystem.com/aas/attendee/index.cfm?ID=5h0LILe* ***)

In order to encourage early registration, we have implemented the following conference registration rate structure: **Register by January 22, 2021 and save $75!**

Category	Early Registration (through Jan 22, 2021)	Registration (beginning Jan 23, 2021)
Full - AAS or AIAA Member	$260	$335
Full - Non-member	$360	$435
Student* - Member	$100	$175
Student* - Non-member	$145	$220
Retired* - Member	$100	$175
Retired* - Non-member	$200	$275

**does not include proceedings CD*

Cancellations must be in writing and received no later than 27 January 2021. There is a $100 cancellation fee.

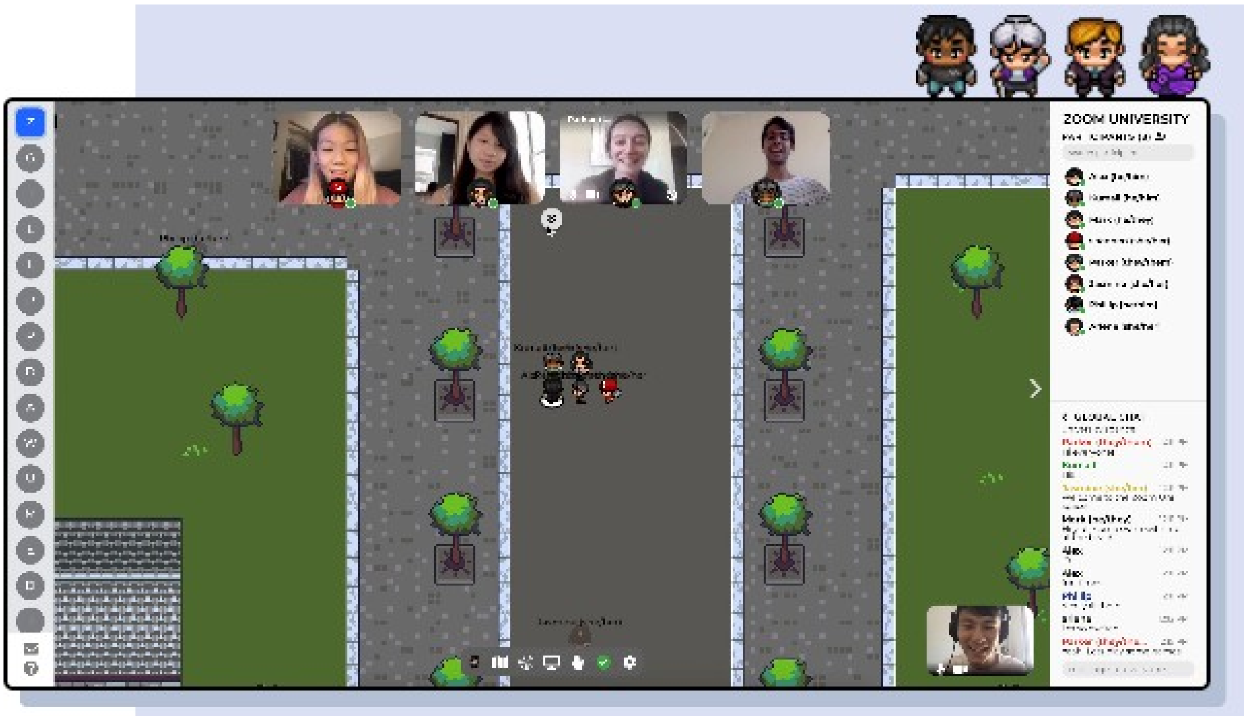
SCHEDULE OF EVENTS

A Welcome and Awards Reception begins on Monday, 1 February at 9:30 AM EST. Technical sessions begin at 10:30 AM EST. A Plenary Session will take place on Wednesday, 3 February from 9:30 AM – 10:15 AM EST. The last technical sessions end at 3:00 PM on Wednesday, 3 February. Presentations during the technical sessions are limited to 8-minute summary presentations followed by 4 minutes of Q&A. All live sessions are moderated by the session chairs, much like during an in-person conference.

Social Activities: One aspect of in-person conferences that everyone misses is the chance to meet and catch up with friends and colleagues from across the astrodynamics community. Just because the conference is virtual doesn't mean we can't be social! For this virtual conference, we are introducing optional social events organized via Gather.Town, an online platform that helps to recreate the organic feeling of in-person events while we are all unable to travel. In Gather, people can move around virtual rooms, have small group conversations (without fear of speaking over other people's chats), and even play various games! We will be providing two options during the conference:

1. Lunch Bunch Rooms (12:00-1:30pm EST all conference days) that are smaller and more intimate, making conversations easier for small groups
2. Afternoon BYOB Happy Hours (3:30-4:30pm EST Monday & Tuesday) in a larger setting to allow people the chance to see many familiar faces

Gather is entirely browser based, so no pesky downloads either. Please see the ***Additional Information*** section later in this program for more information on how to join Gather. We hope you'll join us!



Day	Start	End	Function	Room
Monday 1 February	9:30am	10:00am	Welcome and Awards Reception	Virtual Room #1
	10:30am	12pm	Session 1: Interplanetary Trajectories	Virtual Room #1
	10:30am	12pm	Session 2: Debris Clouds, Debris Densities, and Space Environment	Virtual Room #2
	10:30am	12pm	Session 3: Rendezvous	Virtual Room #3
	10:30am	12pm	Session 4: Satellite Formations & Collision Avoidance	Virtual Room #4
	10:30am	12pm	Session 5: Asteroids I	Virtual Room #5
	Noon	1:30pm	Lunch Bunch Rooms	Gather Town
	Noon	1:30pm	Joint AAS/AIAA Technical Committee Meeting	Meeting Link Sent Via Email
	1:30pm	3:00pm	Session 6: Low Thrust Trajectories I	Virtual Room #1
	1:30pm	3:00pm	Session 7: Attitude Dynamics and Control	Virtual Room #2
	1:30pm	3:00pm	Session 8: Navigation	Virtual Room #3
	1:30pm	3:00pm	Session 9: Atmospheric Reentry Guidance and Control	Virtual Room #4
	1:30pm	3:00pm	Session 10: Artificial Intelligence in Astrodynamics	Virtual Room #5
	3:30pm	4:30pm	BYOB Virtual Happy Hour	Gather Town

Day	Start	End	Function	Room
Tuesday 2 February	10:30am	12pm	Session 11: Low Thrust Trajectories II	Virtual Room #1
	10:30am	12pm	Session 12: Trajectory Design I	Virtual Room #2
	10:30am	12pm	Session 13: Spacecraft Control I	Virtual Room #3
	10:30am	12pm	Session 14: Cislunar Space Situational Awareness	Virtual Room #4
	10:30am	12pm	Session 15: Dynamical System Theory I	Virtual Room #5
	Noon	1:30pm	Lunch Bunch Rooms	Gather Town
	Noon	1:30pm	AIAA Astrodynamics Technical Committee Meeting	Meeting Link Sent Via Email
	1:30pm	3:00pm	Session 16: Trajectory Design II	Virtual Room #1
	1:30pm	3:00pm	Session 17: Spacecraft Control II	Virtual Room #2
	1:30pm	3:00pm	Session 18: Space Object Characterization and Independent Attitude Determination	Virtual Room #3
	1:30pm	3:00pm	Session 19: Asteroids II & Mars	Virtual Room #4
	1:30pm	3:00pm	Session 20: Space Robotics and Autonomous Operation & Lunar	Virtual Room #5
	3:30pm	4:30pm	BYOB Virtual Happy Hour	Gather Town

Day	Start	End	Function	Room
Wednesday 3 February	9:00am	10:00am	Plenary: "Key Considerations to Guarantee Safety of Operations in Space", Dr. Juan Carlos Dolado Pérez	Virtual Room #1
	10:30am	12pm	Session 21: Trajectory Optimization	Virtual Room #1
	10:30am	12pm	Session 22: Formation Flying	Virtual Room #2
	10:30am	12pm	Session 23: Guidance, Navigation, and Control	Virtual Room #3
	10:30am	12pm	Session 24: Orbit Determination	Virtual Room #4
	10:30am	12pm	Session 25: Orbital Dynamics, Perturbations, and Stability	Virtual Room #5
	Noon	1:30pm	Lunch Bunch Rooms	Gather Town
	Noon	1:30pm	AAS Technical Committee Meeting	Meeting Link Sent Via Email
	1:30pm	3:00pm	Session 26: Trajectory Design III	Virtual Room #1
	1:30pm	3:00pm	Session 27: Guidance and Control	Virtual Room #2
	1:30pm	3:00pm	Session 28: Dynamical System Theory II	Virtual Room #3
	1:30pm	3:00pm	Session 29: Space Robotics and Autonomous Operation	Virtual Room #4
	1:30pm	3:00pm	Session 30: Multi Object Tracking	Virtual Room #5
	3:00pm	5:00pm	Conference Administration Subcommittee	Meeting Link Sent Via Email
	3:00pm	5:00pm	Technical Administration Subcommittee	Meeting Link Sent Via Email
	3:00pm	5:00pm	Website Administration Subcommittee	Meeting Link Sent Via Email

SPECIAL EVENTS

WELCOME AND AWARDS RECEPTION

Monday, 1 February 9:30 – 10:00 am

Location: Virtual Room #1

Please join us for welcoming remarks to assist you in your conference experience and a presentation of Best Paper and Breakwell Travel Awards.

PLENARY:

Wednesday, 3 February 9:00 – 10:00 am

Location: Virtual Room #1

Key Considerations to Guarantee Safety of Operations in Space

Dr. Juan Carlos Dolado Pérez, Head of the Space Debris Modelling and Risk Assessment Office at CNES

Juan-Carlos Dolado-Perez is the head of the space debris modelling and risk assessment office at the “Centre National d’Etudes Spatiales” (French Space Agency). Since 2008 he has worked at the system engineering and orbital dynamics sub directorate, where his main research topics concerns the long and middle term re-entry prediction, the long term evolution of the space debris population, the on orbit collision risk assessment, the orbit determination from radar and optical measurements and the uncertainty characterization and propagation.

He is a member of the Inter Agencies Space Debris Committee (IADC)’s French Delegation and of the International Academic of Astronautics (IAA). Juan-Carlos owns a B.S. in Aerospace Engineering from the Madrid’s Polytechnic University and a MSc. in Aerospace Engineering from the Institut Supérieur de l’Aéronautique et de l’Espace (ISAE).

ADDITIONAL INFORMATION

SPEAKER INFORMATION

Authors should have submitted a brief (approximately 50 words or 3 sentences) speaker's bio with their abstract submission. Authors are required to be in their virtual session room 30 minutes prior to the start of their sessions to meet their session chair and work through any technical issues to ensure a smooth session.

For the short presentation, please upload your slides at the speaker portal (https://www.xcdsystem.com/aas/abstract/index.cfm?ID=gge2bwZ) by **January 29 2021, 23:59:59 Eastern Time**.

The longer, pre-recorded, 15-minute video presentation is to be uploaded **by January 29 2021, 23:59:59 Eastern Time** to the speaker portal (https://www.xcdsystem.com/aas/abstract/index.cfm?ID=gge2bwZ). This recording will be available to the registered conference attendees during the entire time of the conference. Please note: recordings longer than 15 minutes will be removed and counted as a no-show if no replacement video complying with the maximum time (15 min) is re-uploaded by the deadline.

For the video presentation, you can record yourself and upload a .mp4 file or use the recording tool provided at the speaker site. Once logged in, please find the button to record or upload your presentation.

For recording instructions and best practices please go to https://x-cd.com/virtual-presentation-guide/. It is recommended to NOT use the safari browser, as tests have shown some hiccups there.

CONFERENCE ATTENDANCE AND PRESENTATIONS

Please see the "How-To-Attend.pdf" and "How-To-Present.pdf" files for specific instructions to access the conference and for presenting at the conference.

Each live presentation is limited to 8 minutes. An additional four minutes is allotted between presentations for audience participation and transition. Session chairs shall maintain the posted schedule to allow attendees the option of joining a parallel session.

"No-Paper, No-Podium" Policy Completed manuscripts 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. If the completed manuscript is not contributed 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 is also acknowledges that he or she is 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), he or she acknowledges 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.

PREPRINTED 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/program/XCtzIQp for registrants who have logged in.

CONFERENCE PROCEEDINGS

All full registrants will receive a CD of the proceedings mailed to them after the conference (extra copies are available for $60 during registration). 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
Aerospace Engineering and Engineering Mechanics
2617 Wichita Street
ASE Building, C0600
Austin, TX 78712
makella@mail.utexas.edu

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-jgcd

Journal of Spacecraft and Rockets
Editor-in-Chief: Dr. Hanspeter Schaub, University of Colorado-Boulder
Manuscripts can be submitted via: https://mc.manuscriptcentral.com/aiaa-jsr

SATISFACTION SURVEY

Registrants are highly encouraged to record their level of satisfaction and conference preferences in an anonymous survey which will be online after the conference with a link provided via email.

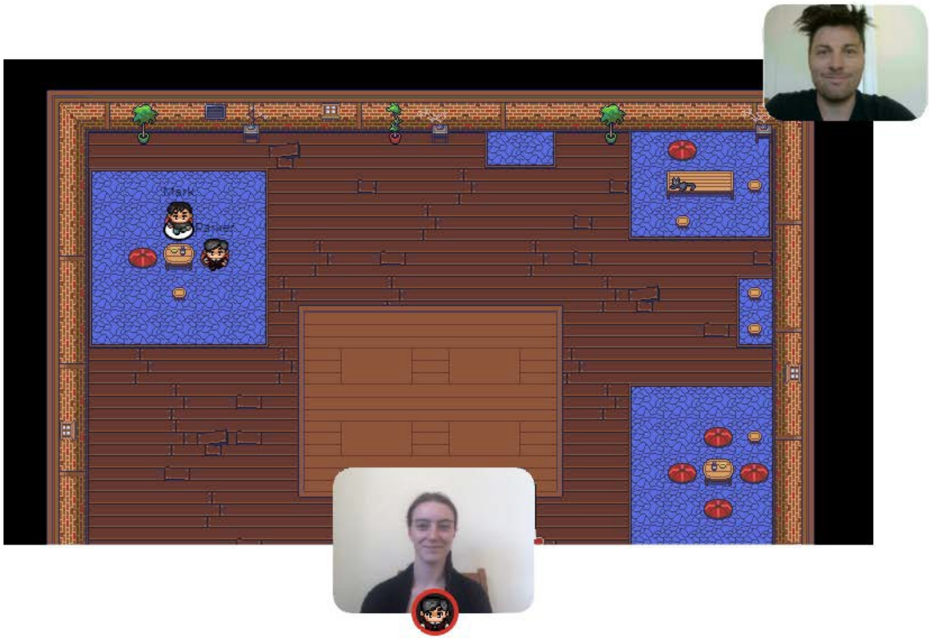
COMMITTEE MEETINGS

Committee meetings are limited to committee members and invited guests. Committee and subcommittee meetings will be held according to the schedule at the beginning of the program. Committee members will be provided a virtual meeting link via email prior to the conference.

GATHER LUNCH BUNCH AND HAPPY HOUR ROOMS

Gather is a wonderful new tool for getting to both explore and chat with other people. It is also a very new tool and has a few quirks. This guide is to help you with the **basics** so you can discover and play on your own. To use the Gather sites set up for the conference, you can click on the links located on the main conference "Lobby" page. Please see the "How-To-Attend.pdf" guide for instructions on how to navigate to the main conference "Lobby" page.

For more information, visit the FAQ: https://gather.town/faq



Conference Etiquette Applies!

- While we do provide spaces for "private" conversation, please be aware that Gather is much like any real-world public space.
- People may overhear your conversation as they move around the space, messages may not remain between two people, etc.
- *Please, act with the professional etiquette like you would during an in-person conference*
- If you have any concerns or complaints about someone's behavior, please contact one of the conference chairs (Jeff Stuart, Angela Bowes, Renato Zanetti, Carolin Freuh) either within Gather or via an alternate means such as email.

What you need:

- A **desktop/laptop** with a **mic** and **camera**.
- A webbrowser (Chrome or Firefox recommended).
- We strongly recommend using **headphones** to help preventfeedback.
- That's it! There's nothing to install, no software to download.

Howit works:

- Gather is a video chat platform that has avatars move around a map. As you get close to other avatars, your video's will pop up and you will be able to chat.
- Move around the space using the **arrow keys**.
- By moving your avatar around you can have spontaneous conversations with those around you. These can be either one-on-one or small groups depending on how many people are around your avatar.

- When your avatar moves closer to an interactable object, there will be a notification that shows up saying 'Press x to interact with -object-'. This can range from informational flyers, playable arcade games, integrated Zoom meetings, and more!

Icon Explanation:

Screen sharing ability

Change your **avatar** character and clothing

Mini map to preview the space you're in

Raise hand feature: good for Q&A in keynotes or classrooms

Opens the **settings** menu:

- Change Name
- Change Audio/Video Devices
- Respawn button to return to start

Not-So-Obvious Features:

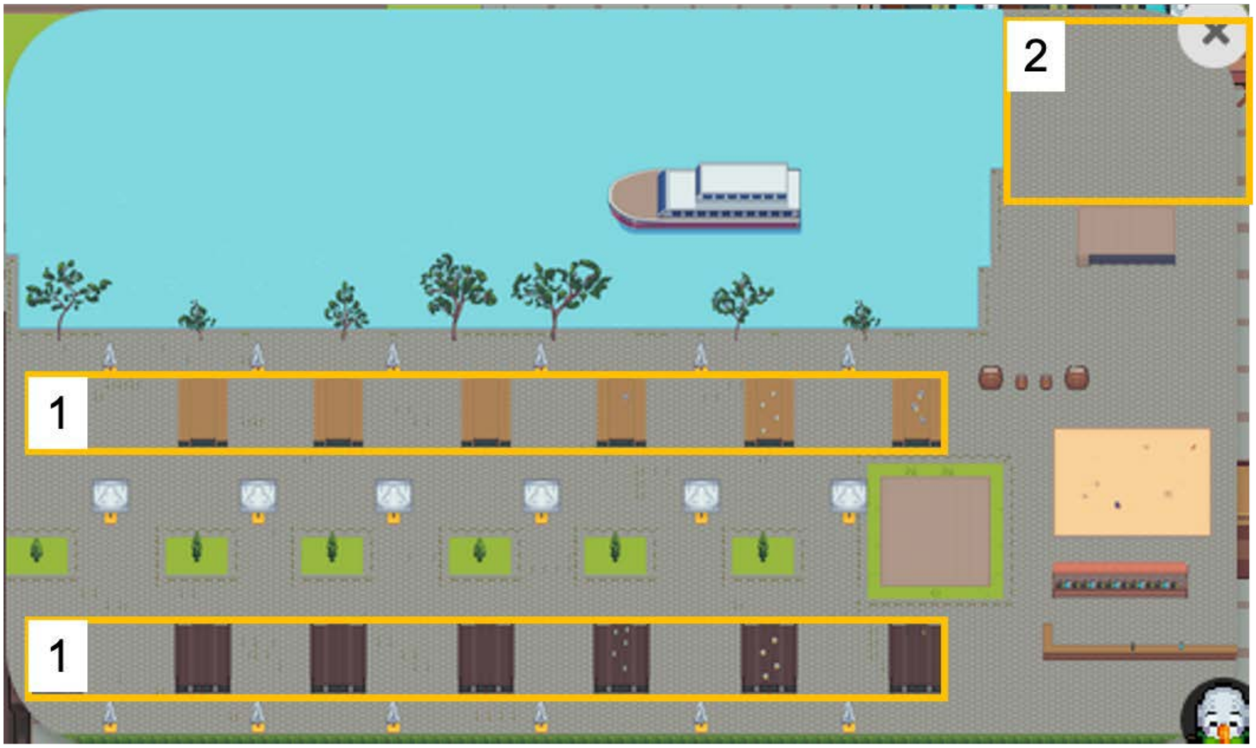
Here are some things you might find useful but aren't immediately obvious.

- There is a **messaging feature** that allows you to message people in three ways:
  1. *individually* by clicking on their name in the participant panel,
  2. *locally* to the people you are video chatting with,
  3. *globally* to all the people in your map.
- There is a **locate feature** to find others by clicking their name in the participant panel.
- Interaction distance is also sometimes altered by **designated** **private spaces**. This allows conversations to only include people inside that space.
- Want to **full screen someone else's video**? Just click on their video.
- Talking to a group of people? Click the down arrows centered below the videos to shift into **grid view**.

Technical difficulties:

- Refreshing the page will fix most things!
  - If that doesn't work, try muting and unmuting your mic and camera in Gather.
  - Check if your browser permitted camera and mic access
  - Additional troubleshooting at https://gather.town/video-issues

Happy Hour Map Guide:



Welcome to the SFMM Happy Hour!

Two Happy Hours have been arranged, Monday & Tuesday, 3:30-4:30pm EST

The Happy Hours are free for conference attendees, but BYOB!

The space for the Happy Hour is meant to be explored, but we want to point out two areas that might be of special interest:

1. The tables here have been set to enable "private" conversations for those standing next to the table. So, feel free to talk without worrying about interrupting other people's conversations! Some of the tables have games at them. We encourage you to play!
2. We've provided some whiteboards with "private" spaces, if you just can't resist the stray technical conversation!

Lunch Bunch Rooms:

We have also provided a limited number of rooms for lunchtime social interactions (or any time, really). In addition to "private" conversation spaces and a few games, we've also provided whiteboards for sidebar technical conversations. The rooms are limited to 25 people per room and are smaller, so please be respectful of other conference attendees!

Feb 1, 2021Virtual Room #1

01 - Interplanetary Trajectories

Chair: Kathleen C. Howell, Purdue University

10:30 **AAS 21-261** **Transfer between planar and 3D Quasi Satellite Orbits around Mars's moon Phobos**
Stefanos Charkoutsis, University of Liverpool; Elisabet Canalias, CNES; Stefania Soldini, University of Liverpool

This research paper is focused on the preliminary design of transfer trajectories between a planar orbit and a spatial orbit around Phobos, as part of the MMX mission. MMX is a mission led by JAXA, to send spacecraft to the two moons of Mars, Phobos and Deimos, in collaboration with the French (CNES) and German (DLR) space agencies, to study their origins. Initially validation of the CR3BP and ER3BP models was conducted, and then the theoretical and numerical minimum and maximum costs were computed for the transfers and compared the results with that of (Canalias, et al., January 2019).

10:54 **AAS 21-300** **Application of Halo Orbit on Extension for Launch Window Limited by Direct Earth-Mars Transfer**
Zhe Xu, Kyushu University; Mai Bando, Kyushu University; Hideaki Ogawa, Kyushu University; Shinji Hokamoto, Kyushu University

This paper aims to propose a design method on resorting to Halo orbit to overcome the problems of high risk and limited launch window, which is common in traditional direct Earth-Mars transfer mission. To overcome the big scale computation problem brought about by this multiple dimension problem, surrogate-assisted design methodology is employed. Meanwhile, GPU parallel computation technique is also adopted to further reduce the computational cost to an acceptable extent. Based on it, structure of solution is investigated in terms of capability and contribution of halo orbits as a phasing orbit to interplanetary transfer.

11:06 **AAS 21-330** **Earth-to-Mars Low Energy Transfers from Cislunar Direct Retrograde Orbits**
Colas Chevailler, ISAE-SUPAERO; Emmanuel Blazquez, ISAE-SUPAERO; Stéphanie Lizy-Destrez

The scope of this research is to propose new impulsive transfer strategies from Earth-Moon DROs to Sun-Mars planar Lyapunov Orbits, making use of low-energy pathways and weak stability boundaries. The trajectory is optimized in three patched Three-Body systems to make use of an intermediary phasing planar Lyapunov Orbit of the Sun-Earth system. Firstly, a new strategy for cost-efficient departure from DROs is showcased, by injection into the unstable invariant manifold of a tangential planar Lyapunov Orbit. Secondly, a systematic hybrid optimization procedure is proposed to design fuel and time efficient DRO-to-Mars trajectories easily corrected in high-fidelity models.

11:18 **AAS 21-295** **DEEP SPACE TRANSFERS OF PIGGY-BACK MICRO SPACE PROBES USING HYBRID ROCKET KICK MOTOR**

Daichi Ito, The Graduate University for Advanced Studies, SOKENDAI; Nishanth Pushparaj, The Graduate University for Advanced Studies, SOKENDAI; Kotaro Fujiwara, Hokkaido University; Yasuhiro Kawakatsu, JAXA / ISAS

Geostationary Transfer Orbit (GTO) is a good launching point for deep space missions. Although "piggy-back" is a low-cost approach for inserting micro space probes into a GTO, the main mission primarily determines GTOs' nature and the launch window. Therefore, the piggy-back probes' kick motor must have the necessary capacity to cope with arbitrary launch dates and GTOs. Preliminary studies suggest that GTO to Moon transfer requires a ΔV of 1.81km/s. This study extends the transfer case to Mars, utilizing an Earth swing-by via 1:1 resonant orbit from a GTO. These results provide useful insights for designing and planning low-cost missions.

11:30 **AAS 21-230** **EVALUATION OF ITERATIVE ANALYTICAL TECHNIQUES FOR THE TRAJECTORY DESIGN OF A DIRECT JUPITER ORBITER MISSION**

Parvathi S P, Indian Institute of Science; Ramanan R V, Indian Institute of Space Science and Technology

For a direct orbiter mission to Jupiter, it is understood that the velocity impulse required will be huge. To surpass this expenditure, usually gravity assist missions are attempted for a Jupiter mission. However, in this research, an evaluation is carried out for the trajectory design of a direct Jupiter orbiter mission. The iterative analytical techniques based on the patched conic and the pseudostate concepts are used to obtain the trajectory design for the minimum energy opportunity of 2022. A comparison is made on the initial states of the departure trajectory and the achieved target parameters.

11:42 **AAS 21-370** **Solar Sail Trajectories for Interstellar Object Rendezvous**

Daniel Miller, Massachusetts Institute of Technology; Damon Landau, Jet Propulsion Laboratory; Richard Linares, Massachusetts Institute of Technology; Benamin Weiss, Department of Earth, Atmospheric and Planetary Sciences; Paulo Lozano, Department of Aeronautics and Astronautics

Using the “statite” concept, this paper presents a potential solar sail mission to study Interstellar Objects (ISOs). These objects are tantalizing scientific targets but challenging to study due to their short lead time and high heliocentric velocities. By using its solar sail to “hover” in place, a statite is able to await the discovery of an ISO and, when called upon, convert the enormous potential energy of its state into the velocity necessary to rendezvous with the object. In this investigation, solar sail trajectories to known ISOs will be produced and launch trajectories to the initial statite state will investigated.

02 - Debris Clouds, Debris Densities, and Space Environment

Chair: Alinda Mashiku, NASA GSFC

10:30 AAS 21-269 Density Waves in Debris Clouds

Ken Chan, Chan Aerospace Consulting

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

10:42 AAS 21-268 Some Topological Properties of Keplerian Parametric Scatter Diagrams of Debris Clouds

Ken Chan, Chan Aerospace Consulting

This paper discusses some topological properties exhibited by scatter diagrams such as semi-major axis/eccentricity, semi-major-axis/inclination and eccentricity/inclination of the debris fragments produced either in a collision between two orbiting objects or the explosion of an orbiting object. These properties are useful in the study of debris clouds such as their evolution and decay of various fragments due to atmospheric drag. The approach circumvents the need to perform time-consuming numerical simulations which mask certain features so important inthe prediction of the life span of these debris clouds. Moreover, it leads to the forecast of density waves and their eventual decay.

10:54 AAS 21-200 Debris Risk Truth Data Generation for Model Validation

Brian Hansen, The Aerospace Corporation

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

11:06 AAS 21-217 Effect of perturbations on orbital density using Eulerian orbit dynamics

Liam Healy, Naval Research Laboratory; Blake Halpin, Naval Research Laboratory; Scott Kindl, Naval Research Laboratory; Patric Hoskins, Naval Research Laboratory

The behavior of object density after a fragmentation has been analyzed using "Eulerian orbit dynamics", our term for the propagation of densities in contrast to the traditional propagation of individual objects. We previously pioneered a technique that propagates the spatial density of orbital objects exactly. In the present work, we show the effects of perturbations, principally the J2 gravitational and atmospheric drag, on orbits in low-earth, geosynchronous, and highly elliptical orbits. The results are compared with unperturbed results on a continuous scale, with the perturbation parameter (such as J2 coefficient) varied from zero (unperturbed), to much larger than realistic values.

11:18 AAS 21-286 Secular Dynamics based Features for the Characterization of Small Debris Clouds after Fragmentation

Di Wu, UC San Diego; Aaron Rosengren

Current characterization of space debris usually neglects fragments smaller than 10cm because of the limited numbers of infrastructure capable of doing so. Yet, the threat from small debris objects could not be less dangerous to satellites than any other debris. This work conducts an investigation for space debris clouds and proposes a set of features based secular dynamics to characterize them. Meanwhile these features' evolutions are further illustrated. As a result, these features allow the representation of small debris clouds and the prediction of their evolution.

11:30 AAS 21-354 Assessing Thermospheric Densities Derived from Orbital Drag Data

Valerie Bernstein, University of Colorado Boulder; Marcin Pilinski, Laboratory for Atmospheric and Space Physics, CU Boulder; Eric Sutton, University of Colorado Boulder

Two-Line Element (TLE) entries provide an expansive record of orbital element information for most known Earth-orbiting objects and can be used to derive thermospheric densities. We compare TLE-derived and accelerometer-derived densities for 8+ years of CHAMP and GRACE satellite data. Results indicate that TLE processing choices, as well as the relative positioning of the twin GRACE satellites, significantly impact agreement between the different density datasets. Additionally, TLE density variability is greater in low-drag environments. This analysis reveals the uncertainty inherent in long-term density datasets inferred from TLEs used to construct empirical models, which are then fed into orbit determination schemes.

11:42 AAS 21-340 Density estimation using second-order Gauss Markov processes

Vishal Ray, CU Boulder; Daniel Scheeres, University of Colorado Boulder; Eric Sutton, University of Colorado Boulder; Marcin Pilinski, Laboratory for Atmospheric and Space Physics, CU Boulder

Atmospheric density estimates derived from satellite data play an important role in determining a satellite's location in orbit and studying the evolution of the Earth's atmosphere. But they are plagued by biases resulting from simplifying assumptions pertaining the satellite drag-coefficient. In this work, we leverage previous work on simultaneous estimation of atmospheric density and ballistic coefficient from satellite tracking data using first-order Gauss-Markov processes. We extend the method to utilize second-order Gauss Markov processes that are more suitable for periodically varying parameters and estimate the drag-coefficient using Fourier models.

11:54 AAS 21-415 Impact of Driver and Model Uncertainty on Drag and Orbit Prediction

Richard Licata, West Virginia University; Piyush Mehta, West Virginia University; W. Kent Tobiska, Space Environment Technologies

Space Weather (SW) has a strong influence on satellite tracking, orbital decay, and collision avoidance in low Earth orbit (LEO). Specifically, satellite position Probability Density Functions (PDFs) essential for probability of collision, Pc, estimates are heavily dependent on drag. These PDFs are used in satellite conjunction analyses; therefore, confidence in them is paramount. However, these density forecastshave multiple sources of uncertainty that can lessen our confidence in the resulting PDFs. These include SW driver uncertainty, model uncertainty, and subgrid uncertainty. In this paper, we quantify the impact of both SW driver uncertainty and model uncertainty and analyze their contributions.

Feb 1, 2021Virtual Room #3

03 - Rendezvous

Chair: Fabio Curti, School of Aerospace Engineering, Sapienza University of Rome

10:30 **AAS 21-209** **Bearings-Only Guidance for Rendezvous in a Cis-Lunar NRHO**

Giordana Bucchioni, University of Pisa Dip.Ingegneria Informazione; Mario Innocenti, University of Pisa - Department of Information Engineering; Fabio D'Onofrio, University of Pisa, Dip. Ingegneria dell'Informazione

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

10:42 **AAS 21-235** **Analytical Description of Relative Position and Velocity on J2-Perturbed Eccentric Orbits**

Matthew Willis, Stanford University; Simone D'Amico, Stanford University

A new solution is introduced for the relative position and velocity of two spacecraft on eccentric orbits perturbed by Earth oblateness. The equations of relative motion subject to an arbitrary perturbing force are derived and this general framework is used to develop a partial solution for the case of perturbation by the second zonal harmonic of Earth's gravitational potential. The performance of the new solution is compared with several prominent translational and orbital element-based solutions from the literature, and the inability of variation of parameters to produce a complete, closed-form solution for the J2 corrections is discussed.

10:54 **AAS 21-281** **Non-Cooperative Rendezvous and Proximity Operations for Active Debris Removal Missions**

TAKAHIRO SASAKI, Japan Aerospace Exploration Agency; Naomi Murakami, JAXA; Yu Nakajima, JAXA; Moeko Hidaka; Ryo Nakamura, Japan Aerospace Exploration Agency; Toru Yamamoto, Japan Aerospace Exploration Agency

As the amount of debris in orbit increases, so does the risk of collisions and their seriousness. One solution receiving increased attention is active debris removal (ADR). The first step in such missions would be to approach the debris. This study addresses the practical rendezvous scenario for the ADR mission and clarifies the requirements for the navigation system, by using the Linear Covariance Analysis, while newly taking bias errors into account. It also considers trajectory safety in both nominal and off-nominal situations. Finally, it is shown that the proposed rendezvous trajectory is sufficiently safe from the viewpoint of collision.

11:06 **AAS 21-357** **Optimal Trajectory Control of J2 Perturbed Spacecraft Relative Motion in Elliptical Orbit**

Ayansola Ogundele, National Space Research and Development Agency; Olufemi Agboola, National Space Research and Development Agency, Nigeria

The proper functioning of aerospace systems and their ability to achieve the mission objectives depend largely on proper understanding of their relative motion dynamics and ability to keep them in the required mission operation configurations through proper control. In this paper, nonlinear dynamics and control of J2 perturbed spacecraft formation flying are developed via Euler-Lagrange and State Dependent Riccati Equation (SDRE) approach. J2 perturbed nonlinear dynamic relative motion model containing quadratic nonlinear terms is obtained from the original nonlinear J2 perturbed equation. Then, SDRE technique is applied to the model. Efficiency of the controller is validated using numerical simulations.

11:18 **AAS 21-419** **Challenge Problem: Assured Satellite Proximity Operations**

Christopher D. Petersen, Air Force Research Laboratory; Kerianne Hobbs, Air Force Research Laboratory; Kendra Lang, Verus Research; Sean Phillips, AFRL

Assuring safety of a spacecraft during autonomous rendezvous, proximity operations, and docking is a non-trivial, multi-constraint challenge. To address this, we formulate a challenge problem relating to autonomous rendezvous and docking of a basic 6U CubeSat model with thrust in one axis, a reaction wheel for attitude control, and a gimballed sensor. To assure safety of the vehicle during operations, a variety of constraints are introduced. Several different solutions to the challenge problem are discussed, with benefits and disadvantages being highlighted.

11:30 **AAS 21-423** **Autonomous Satellite Rendezvous and Proximity Operations via Model Predictive Control Methods**

Anonto Zaman, Georgia Institute of Technology; Alexander Soderlund, National Academy of Sciences / Air Force Research Laboratory; Christopher D. Petersen, Air Force Research Laboratory; Sean Phillips, AFRL

This work examines the autonomous rendezvous, proximity operations, and docking (ARPOD) problem wherein a "chaser" spacecraft with a single thruster must maneuver and dock with a "target" spacecraft whilst maintaining safety constraints. The challenge lies in the fact that the chaser satellite is underactuated, and there is coupling in both its translational and rotational dynamics. To drive the inputs of the chaser we leverage non-linear model predictive control (MPC) in order to construct an efficient control policy while incorporating nonlinear dynamics and constraints. In-depth simulation analyses demonstrate successful safe docking through this MPC-driven approach.

11:42 **AAS 21-438** **Forced Relative Motion Using the Clohessy-Wiltshire Equations**

Brendan Hennessey Rose, USAFA; Blair F. Thompson, The Aerospace Corporation; Daniel Showalter

In this paper we present a novel method for the development and analysis of forced motion relative trajectories between two spacecraft. The method is based on Lambert targeting in the natural relative motion space of the Clohessy-Wiltshire (CW) equations. The desired relative motion trajectory is discretized over time of flight. The method can then be used to determine the feasibility of the desired relative trajectory compared to the thrust availability for a particular spacecraft, and to modify

the trajectory and time of flight to satisfy maneuvering constraints such as line of sight, position relative to the sun, etc. This method

Feb 1, 2021Virtual Room #4

04 - Satellite Formations & Collision Avoidance

Chair: Christopher Roscoe, Tiger Innovations

10:30 **AAS 21-410** **Optimizing Formation Flying Orbit Designs**
James Ragan, California Institute of Technology; Soon-Jo Chung, California Institute of Technology; Kai Matsuka, California Institute of Technology; Marco Lavelle, JPL; Razi Ahmed, JPL; Ilgin Seker, JPL

Groups of spacecraft flying in formation in Earth orbit have the potential to perform more complex tasks and produce higher quality science but introduce increased design complexity. This study attempts to optimize the design of spacecraftformations subject to dynamic constraints in the context of an Earth observing Synthetic Aperture Radar mission, in terms of the quality of science produced. Building on preliminary trajectories found using genetic algorithm-based methods, a simplified version of the design problem will be solved to give an analytic solution, to be used to approximate the global solution via further machine learning based algorithms.

10:42 **AAS 21-417** **Structural Design and Impact Analysis of a 1.5U CubeSat on the Lunar Surface**
Christopher Hays, Embry-Riddle Aeronautical University; Troy Henderson, Embry-Riddle Aeronautical University; Daniel Posada, Embry-Riddle Aeronautical University; Aryslan Malik, Embry-Riddle Aeronautical University

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

10:54 **AAS 21-313** **Securing Distributed Micro Satellites from Cyber-attacks**
Mizanul Chowdhury, MIT

The large-scale development and deployment of small satellite systems in the modern aerospace sector motivates the parallel development of new flight software and avionics systems to meet the demands of modern spaceflight operations. Cyber-attacks are a growing threat to future robots. The shift towards automatization has increased relevance and reliance on robots. Securing robots has been secondary or ternary priority and thus robots are vulnerable to cyber-attacks. I am proposing a federated policy enforcement point using Attribute Based Access Control (ABAC) based architecture, using cryptography mechanism, which addresses the most common ROS safety issues.

11:06 **AAS 21-361** **STATE-SPACE CONTROLLER FOR LEO, LOW-THRUST SATELLITE CONSTELLATIONS**

Mario Contreras, MIT; David Arnas, Massachusetts Institute of Technology; Richard Linares, Massachusetts Institute of Technology

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

11:18 AAS 21-276 Determination of Efficient Quantities of Interest for Space Situational Awareness and Adaptive Monte Carlo

Andrew VanFossen, The Ohio State University; Mrinal Kumar, The Ohio State University

Space situational awareness (SSA) integrates space surveillance, environmental monitoring, the current status of satellite systems, and analysis of the space domain to provide decision-making entities with a quantifiable and timely body of evidence. The feasibility of utilizing probability of collision as a quantity of interest within an adaptive Monte Carlo (AMC) platform to controltransient performance is investigated. The computationalefficiency of each method is evaluated and compared as timely and actionable intelligence is a requirement of SSA. A parallel approach is also implemented to further alleviate computational bottlenecks within the AMC platform.

11:30 AAS 21-311 Design of Collision Avoidance Maneuvers using Optimal Control Theory and Convex Optimization

Álvaro Martínez Chamarro, ISAE-SUPAERO; Carlos Belmonte Hernandez, ISAE-Supaero; Roberto Armellin, ISAE-SUPAERO

This work presents two methods to compute low-thrust collision avoidance maneuvers for short term encounters. The first method is based on a minimum-energy optimal control problem. In the second method, the design of the maneuver is formulated as a convex optimization problem. In both cases, constraints on either an approximated value of the collision probability, the miss distance, or the maximum collision probability are considered. The methods are compared on a large set of realistic conjunctions in low Earth Orbit.

11:42 AAS 21-440 Velocimeter LIDAR Systems for Automated Rendezvous, Proximity Operation and Debris Removal Applications

Manoranjan Majji, Texas A&M University, College Station

11:54 AAS 21-267 Collision Probability for General Spacecraft

Ken Chan, Chan Aerospace Consulting

This paper deals with the formulation of analytical expressions (up to the fourth order in a Taylor's series expansion of the Gaussian probability density function) for computing the collision probability of a general spacecraft whose cross-section can be described by combinations of circles, ellipses, rectangles, parallelograms and polygons of any shape. These polygons may be convex or concave simply connected or even multiply connected regions. Since any spacecraft cross-section can be decomposed into these elemental cross sections to any degree of accuracy, this formulation yields the collision probability of an actual collision cross-section of an entire spacecraft with space debris.

Feb 1, 2021Virtual Room #5

05 - Asteroids I

Chair: Roberto Furfaro, The University of Arizona

10:30 **AAS 21-206** **Trajectory Evolution of the Spherical Rover in Different Asteroid Terrains**
Ziwen Li, Beijing Institute of Technology; Xiangyuan Zeng, Beijing Institute of Technology

The paper presents the trajectory evolution of the sphericalrover under the different asteroid terrains. As for the rubble-pile asteroids, the influence of topography on the hopping rover should be taken into account. Taking comet 133P as the central body, three different local terrains are constructed based on the corresponding smooth polyhedron model. The large-scale trajectories are simulated to analyze the evolution of the sphericalrover in these different terrains. The distribution of the terminal longitudes and latitudes of trajectories are recorded and compared to discuss the influence of asteroid terrain on the spherical rover.

10:42 **AAS 21-227** **HIGH-FIDELITY SIMULATIONS OF SMALL BODY LANDERS WITH ARBITRARY SHAPES BASED ON THE POLYGONAL CONTACT**
Yonglong Zhang, Tsinghua University; Tongge Wen, Beijing Institute of Technology; Ziwen Li, Beijing Institute of Technology; Xiangyuan Zeng, Beijing Institute of Technology; Li Junfeng

The high-fidelity simulations of a lander on and above the surface of a small body is still an open problem. In this study, both the lander and the small body are modeled as polyhedrons. The Polygonal Contact Model (PCM) is used to calculate the contact force and torque between landers and small bodies. Together with orbital and attitude dynamics, the 6 degrees of freedom motion of a lander on and above the surface of a small body can be simulated. More details about them are presented in our full paper. The advantages of our method are also given.

10:54 **AAS 21-296** **Asteroid Landing with a Solar Sail: Lander Deployment and Sail Descent to Surface**
Iain Moore, Universityof Glasgow; Colin McInnes, Universityof Glasgow; Matteo Ceriotti, University of Glasgow

Solar sails have been proposed as the primary propulsion system for multiple Near-Earth Asteroid (NEA) rendezvous missions. The propellant-less nature of the sail makes then uniquely placed to achieve the high energy requirements of such a mission. This work investigates the landing phase of the mission, presenting both the lander deployment from the sail and the descent of the sail to the surface of the asteroid. Deployment of significant mass from the sail brings a change in sail performance. This brings a change in the dynamics of the system, which is investigated here.

11:06 **AAS 21-378** **On-board small-body semantic segmentation based on morphological features with U-Net**

Mattia Pugliatti, Politecnico di Milano; Michele Maestrini, Politecnico di Milano; Pierluigi Di Lizia, Politecnico di Milano; Francesco Topputo, Politecnico di Milano

Small-bodies exhibit a great variability in morphological features which are often unknown a priori, but rich in information that can be exploited for landing, planning and navigation. However, obtaining a database with such features often involves labor intensive processes. This work proposes a methodology that exploits image rendering and processing techniques which allows to automatize the labelling of semantic segmentation of small-bodies' procedurally generated surface features. The database is then used to train a Convolutional Neural Network for semantic segmentation, whose performances are evaluated in 3 scenarios of growing complexity, concluding with an analysis of real images.

11:18 **AAS 21-442** **End to End Asteroid ISRU Using an On-Orbit CubeSat Centrifuge**

Jekan Thangavelautham, University of Arizona

In this paper, we present a coherent plan to combine several existing component technologies to simulate asteroid surface conditions in space on a 12U CubeSat using a mature, low-speed centrifuge laboratory. Using this centrifuge, our development plan will prove the principle feasibility of an excavating mechanism design (1) to access and continuously collect regolith on an asteroid surface using a bucket wheel excavator and (2) provide process technologies to extract water (as a resource). Our approach of simulating an asteroid surface using a relatively simple centrifuge concept offers a unique, low-cost, low-risk alternative to further refine and validate asteroid ISRU technology.

11:30 **AAS 21-443** **Visual Reconnaissance of Tumbling Asteroids with Mother Daughter Swarms**

Jekan Thangavelautham, University of Arizona

Small satellites are emerging as a promising new tool for interplanetary exploration. This work develops small satellite swarm architectures for reconnaissance mission concepts to tumbling asteroids. The tumbling dynamics of the asteroid, coupled with its irregular shape, make the mission concept design process complex and unintuitive. We present the design of swarm architectures that minimized the number of spacecraft required and generate a global surface map of the asteroid from multiple flyby encounters. The presented architectures are then demonstrated using a case study of a simulated mission concept to the asteroid 4179 Toutatis.

11:42 **AAS 21-411** **The Perturbative Effects of Gas Drag at Active Comets: Equations of Motion for the Mean Elements under Periodic Inverse-Square Perturbations**

Mark Moretto, University of Colorado Boulder; Jay McMahon, University of Colorado Boulder

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

06 - Low Thrust Trajectories I

Chair: Natasha Bosanac, University of Colorado, Boulder

13:30 **AAS 21-231** **Low Thrust Trajectory Design with Convex Optimization for Libration Point Orbits**
Yuki Kayama, Kyushu University; Kathleen C. Howell, Purdue University; Mai Bando, Kyushu University; Shinji Hokamoto, Kyushu University

Convex optimization has been attracting attention because it is highly robust and requires short computation times. This paper considers to apply the convex optimization to trajectory design using three-body dynamics in cis-lunar space and verify that it does work well even for the region near the Lagrange points involves instability and nonlinearity. Specifically, the convex optimization scheme is applied in the transfer from a halo orbit to the near-rectilinear halo orbit which is a periodic orbit defined in the CR3BP. As a further step, the transfer problem is transitioned to an ephemeris model.

13:42 **AAS 21-242** **FUEL OPTIMIZATION OF LOW-THRUST SATELLITES USING A SEMI-ANALYTIC APPROACH**
Axel Garcia, MIT; Richard Linares, Massachusetts Institute of Technology; Paul J. Cefola, University at Buffalo (SUNY); Zachary Folcik, Arlington, MA; David Gondelach, Massachusetts Institute of Technology; Christopher Jewison, Draper; Juan Félix San-Juan, University of La Rioja

The main goal of this research is to optimize low-thrust collision avoidance maneuvers for both the probability of collision between satellites and the propellant expenditure considering a J2 perturbation model. An indirect control method combining the minimum fuel optimal control problem with the probability of collision taken as a terminal constraint is presented in this paper. We apply analytical and semi-analytical propagation techniques to efficiently compute optimal collision avoidance maneuvers. These techniques will be compared with another implementation of the indirect method using a full numerical solution. Efficiency, accuracy robustness and computational speed trades among these models are analyzed.

13:54 **AAS 21-273** **Exploration of Low-Thrust Lunar Swingby Escape Trajectories**
Jackson Shannon, University of Maryland; Donald Ellison, NASA Goddard Space Flight Center; Christine Hartzell

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

14:06 **AAS 21-302** **A Hybrid Closed-Loop Guidance Strategy for Low-Thrust Spacecraft Enabled by Neural Networks**

Nicholas LaFarge, Purdue University; Kathleen C. Howell, Purdue University; Richard Linares, Massachusetts Institute of Technology

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

14:18 AAS 21-315 Autonomous Guidance for Multi-revolution Low-thrust Orbit Transfer via Reinforcement Learning

Hyeokjoon Kwon, Korea Advanced Institute of Science and Technology (KAIST); Snyoll Oghim, KAIST ; Hyochoong Bang, Korea Advanced Institute of Science and Technology (KAIST)

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

14:30 AAS 21-331 INITIAL MANEUVER TARGETING AROUND SMALL BODIES USING LOW-THRUST PROPULSION

Donald Kuettel, Colorado Center for Astrodynamics Research; Jay McMahon, University of Colorado Boulder

Low-thrust propulsion is natural choice for spacecraft propulsion around small bodies. However, the finite, continuous maneuvers associated with low-thrust propulsion are not able to be accomplished with a traditional open-loop GNC ap- proach. As such, an autonomous spacecraft GNC architecture is necessary. This paper focuses on developing a variety of autonomous maneuver targeting capabil- ities in the small body environment using low-thrust propulsion. This is accom- plished by using a Lambert solver, a parametric bilinear tangent control law cou- pled with a Newton-Raphson predictor-corrector, and a Brent-Dekker root-finding method.

14:42 AAS 21-344 A MODIFIED ORBIT CHAINING FRAMEWORK FOR LOW-THRUST TRANSFERS BETWEEN ORBITS IN CISLUNAR SPACE

Bonnie Prado Pino, Purdue University; Kathleen C. Howell, Purdue University; David Folta, NASA Goddard Space Flight Center

In an effort to explore further extended mission options for the Lunar IceCube (LIC) spacecraft, new interest arises into the problem of constructing a general framework for initial guess generation of low-thrust trajectories in cislunar space, that is independent of the force models in which the orbits of interest are defined. In this investigation, a generalized strategy for constructing initial guesses for low-thrust spacecraft traveling between lunar orbits is presented. These trajectories are converged as mass-optimal solutions in lower fidelity models, that are easily transitioned to a higher fidelity ephemeris model, while evolving entirely within the cislunar region.

14:54 **AAS 21-350** **Toward On-Board Guidance of Low-Thrust Spacecraft in Deep Space Using Sequential Convex Programming**

Christian Hofmann, Politecnico di Milano; Francesco Topputo, Politecnico di Milano

A robust and lightweight algorithm based on convex programming is developed to solve the low-thrust fuel-optimal trajectory optimization problem. We convexify the problem and use a hp-adaptive flipped Radau Pseudospectral discretization. Switching times are determined and added as optimization variables in a subsequent optimization process to obtain accurate on-off control structures. The overall robustness is assessed by varying the quality of the initial guess through a shape-based method and compared to results in the literature and state-of-the-art solvers. The method is a promising first step towards autonomous guidance in real space missions due to its rapid speed and excellent robustness.

Feb 1, 2021Virtual Room #2

07 - Attitude Dynamics and Control

Chair: Andrew J. Sinclair, Air Force Research Laboratory

13:30 **AAS 21-237** **Design of Time-Optimal Slew Maneuvers with Boolean Star Tracker Availability Constraints**

Elliott VonWeller, Naval Postgraduate School; Mark Karpenko, Naval Postgraduate School; Ronald J. Proulx, Naval Postgraduate School

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

13:54 **AAS 21-371** **Modified State Observer for Attitude Synchronization of Formation Flying Spacecraft**

Garba Subedi, Wichita State University; Atri Dutta, Wichita State University

This paper considers the problem of attitude tracking for synchronization of spacecraft in formation flying network, taking into consideration communication time delay, system uncertainties and external disturbances. Our methodology utilizes a graph theory based model for the communication network to determine the desired reference attitude profile for synchronization and an inverse-controller design for tracking the desired attitude profile. The inverse controller is augmented with Chebyshev neural network based modified state observer to account for system uncertainties and external disturbances. Numerical simulations are presented to demonstrate the performance of the controller.

14:06 **AAS 21-387** **EXAMINTION OF MAGNETIC DIRECTIONAL CONTROL BY FORCE USING SUPERCONDUCTING DIAMAGNETIC EFFECT**

Shogo Tochimoto, Graduate School of Frontier Sciences, The University of Tokyo, Master 2nd grade; Sakai Shin-ichiro, Japan Aerospace Exploration Agency

In recent years, the image resolution required for space telescopes has dramatically increased, and it is necessary to prevent vibration disturbance and heat generated from various devices from propagating to the observation equipment. Therefore, our laboratory proposes a mechanism that separates the telescope part and the bus part equipped with various devices and passively controls the relative position using magnetic flux pinning. Regarding this mechanism, we estimated and made an experiment with the repulsive and attractive force due to the superconducting diamagnetic effect.

14:30 **AAS 21-409** **Attitude State Uncertainty Propagation Using Stochastic Expansions**

Brandon Jones, The University of Texas at Austin; Trevor Wolf, The University of Texas at Austin

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

Feb 1, 2021Virtual Room #3

08 - Navigation

Chair: Brian Gunter, Georgia Institute of Technology

13:30 **AAS 21-211** **The Evolution of Deep Space Navigation: 2014-2016**

Lincoln Wood, Jet Propulsion Laboratory, Caltech

The exploration of the planets of the solar system using robotic vehicles has been underway since the early 1960s. During this time the navigational capabilities employed have increased greatly in accuracy, as required by the missions' scientific objectives and as enabled by improvements in technology. This paper is the eighth in a chronological sequence dealing with the evolution of deep space navigation, covering the time interval 2014 to 2016. The paper focuses on the observational techniques used to obtain navigational information, propellant-efficient means for modifying spacecraft trajectories, and the computational methods employed, tracing their evolution through 11 planetary missions.

13:42 **AAS 21-254** **Spacecraft Terrain Relative Navigation with Synthetic Aperture Radar**

Bryan Pogorelsky, The University of Texas at Austin; Renato Zanetti, The University of

Texas at Austin; Jingyi Chen, The University of Texas at Austin; Scott Jenkins, Sandia National Laboratories

A spacecraft terrain relative navigation system is presented relying on measurements obtained from a synthetic aperture radar that are fused with inertial measurements and attitude determination system data in a multiplicative extended Kalman filter. The method of processing the SAR images to retrieve measurements for the navigation filter is shown, including autofocusing and image geolocation steps. Monte Carlo simulation results are presented demonstrating that the SAR based terrain relative navigation system produces consistent state estimates and successfully bounds, or in some instances, significantly reduces the navigation uncertainty of the spacecraft throughout its trajectory by up to 98%.

13:54 **AAS 21-266** **Nonlinear Filtering with Intrinsic Fault Resistance**

Gunner Fritsch, Texas A&M University; Kyle DeMars, Texas A&M University

Fault tolerance methods are critical to spaceflight navigation systems, where residual editing is the most common practice to screen out erroneous sensor data. This work investigates an alternative approach, where sensor returns classified as faulty are not simply rejected, but are accounted for within the measurement model of the sensor, ultimately leading to a filter with intrinsic fault resistance. Several different faulty measurement models are examined by comparing the proposed filter to a baseline filter outfitted with residual editing, where analysis is performed to test relative performance, robustness, and approximation ability of the proposed filter.

14:06 **AAS 21-298** **Position Estimation Method by Asteroid Shape Images and Image Coding Method for On-board Optical Navigation**

Shuya Kashioka, SOKENDAI; Genki Ohira, SOKENDAI; Yuki Takao, Japan Aerospace Exploration Agency; Takatoshi Iyota, Soka University; Yuichi Tsuda, Japan Aerospace Exploration Agency

Optical navigation is one of the most rising technologies for the autonomous control of deep space exploration. It is difficult to perform image matching actual images with pre-set images because the appearance of boulders or its shading varies depending on the illumination conditions or the position and attitude of the spacecraft. In this paper, we describe a method for predefining shadow map relating to an asteroid shape model, then defining the regions to be arbitrarily selected image matching. We obtain results that pixel errors are within about one pixel on the image coordinates in shaded object image varying SAP angles

14:18 **AAS 21-359** **Relative Navigation Using A Planet's Illumination Conditions**

Kalani Danas Rivera, Mechanical and Aerospace Engineering, Cornell University; Mason Peck

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

14:30 **AAS 21-383** **Navigation about irregular bodies through segmentation maps**

Mattia Pugliatti, Politecnico di Milano; Francesco Topputo, Politecnico di Milano

Small-bodies exhibit a great variability in terms of morphological features, containing rich information that can be exploited amongst other things for autonomous optical navigation. Observables can be taken from the body's outline or from correlation with natural features. In an attempt to strike a balance between the two family of techniques, in this work an end-to-end navigation algorithm operating on segmentation maps is illustrated. Two different architectures are presented and their performances are evaluated in close-proximity scenarios about Didymos, Lutetia and HW1, assuming the shape model of the bodies is available beforehand.

14:42 **AAS 21-321** **Gaussian Mixture Particle Flow Modeling Using Information Potential**

Kari Ward, Missouri University of Science and Technology; Kyle DeMars, Texas A&M University

Recursive filtering methodologies typically require some form of model to define the underlying probability density function (pdf). One such filter family, particle flow, introduces an update ``dynamics'' model to describe the evolution of the pdf over an update. Implementing a Gaussian mixture model for the pdf allows for estimation in a wide array of problems and increases the capabilities of the particle flow framework. This work builds upon previous research that leverages the incorporation of information to define a flow based on information potential to account for changes and interactions in the Gaussian mixture model.

14:54 **AAS 21-413** **Navigation at Active Comets: The Time Varying and Stochastic Coma**

Mark Moretto, University of Colorado Boulder; Jay McMahon, University of Colorado Boulder

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

Feb 1, 2021Virtual Room #4

09 - Atmospheric Reentry Guidance and Control

Chair: Pradipto Ghosh, Northrop Grumman Corporation

13:30 **AAS 21-201** **Numerical Predictor-Corrector Based Guidance Scheme for Aero-Gravity Assist at Titan for Enceladus Missions**

Daniel Engel, University of Illinois at Urbana-Champaign Department of Aerospace Engineering; Soumyo Dutta, NASA Langley Research Center; Zachary Putnam, University of Illinois at Urbana-Champaign

The Fully Numerical Predictor-Corrector Aerocapture Guidance algorithm was modified to work with a direct force control blunt body vehicle, executing an aero-gravity assist maneuver at Titan to enter a Saturnian orbit and conduct fly-by at Enceladus. Additionally, a proportional-integral-derivative controller was implemented to command sideslip angles for control of the orbital inclination. Numerical simulation showed the developed guidance scheme was capable of minimizing the energy and inclination error at atmospheric exit, allowing Saturnian moon tour trajectories and Enceladus exploration at a small delta-V cost, on the order of 100 m/s in the nominal case.

13:42 **AAS 21-202** **Flight Control Methodologies for Neptune Aerocapture Trajectories**
Rohan Deshmukh, Purdue University; David Spencer; Soumyo Dutta, NASA Langley Research Center

In this work, a comparison of potential flight control methodologies for a Neptune aerocapture mission are presented. Lifting trajectories pertaining to bank angle modulation and direct force control as well as ballistic trajectories pertaining to continuously-variable drag modulation are investigated. A parametric study of vehicle configurations is explored to quantitatively compare the flight envelope between lifting and ballistic trajectories. A closed-loop numerical predictor-corrector aerocapture guidance architecture is utilized to unify each flight control technique for trajectory comparisons. Results from a series of Monte Carlo simulations of blunt body Neptune aerocapture trajectories using each flight control methodology are presented.

13:54 **AAS 21-306** **Nonlinear Set-Membership Filtering-Based State Estimation of Reentry Vehicles**
Diganta Bhattacharjee, The University of Texas at Arlington; Kamesh Subbarao, University of Texas at Arlington

We propose a nonlinear set-membership filtering-based state estimation technique for reentry vehicles. The recursive set-membership filter utilizes the state dependent coefficient parameterization to acquire a pseudo-linear description of the governing nonlinear system. At every recursion, the filter requires solutions to two convex optimization problems and these solutions can be efficiently obtained. We have included details of the filter design, the nonlinear motion model for the reentry vehicle, and the nonlinear measurement model in the extended abstract. In the final version, we would include simulation results corresponding to the set-membership filter and would provide comparisons with other nonlinear state estimation techniques.

14:06 **AAS 21-308** **Analytical Guidance for Mars Aerocapture via Drag Modulation**
Ibrahim Halil Cihan, University of Missouri, Columbia; Craig Kluever, University of Missouri

A new analytical predictor-corrector guidance algorithm has been developed for the Mars aerocapture problem. Ballistic coefficient is the only control variable for shaping the vehicle's flight path. Velocity during the aerocapture maneuver is modeled by a hyperbolic tangent function of flight-path angle. This formulation results in a closed-loop control law for ballistic coefficient. Guidance periodically updates the velocity profile so that the correct exit conditions are achieved. Two different apoapsis-targeting scenarios are investigated for the Mars aerocapture problem. Monte-Carlo simulations demonstrate the performance and robustness of the proposed algorithm.

14:30 **AAS 21-400** **Stochastic Predictor-Corrector Guidance**

Jay McMahon, University of Colorado Boulder; Davide Amato, University of Colorado Boulder

Many guidance algorithms are built on a predictor-corrector algorithm for adjusting guidance parameters to meet terminal trajectory constraints. However these methods classically ignore the fact that the system is in fact stochastic as they solve for the guidance solution. In this paper, we discuss recent developments in a robust predictor-correctormethodology for addressing the stochastic nature of guidance problems. This uncertainty is due to the fact that the navigation solution is imperfect, as well as considering uncertainty in the dynamic models and vehicle performance parameters. We demonstrate the methods on EDL and orbital transfer problems.

Feb 1, 2021Virtual Room #5

10 - Artificial Intelligence in Astrodynamics

Chair: Peter Lai, LinQuest Corporation

13:30 **AAS 21-216** **Designing Impulsive Station-Keeping Maneuvers near a Sun-Earth L2 Halo Orbit via Reinforcement Learning**

Stefano Bonasera, CU Boulder; Ian Elliott, University of Colorado Boulder; Christopher Sullivan, Colorado Center for Astrodynamics; Natasha Bosanac, University of Colorado, Boulder; Nisar Ahmed, University of Colorado Boulder; Jay McMahon, University of Colorado Boulder

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

13:42 **AAS 21-249** **Image-Based Lunar Landing Hazard Detection via Deep Learning**

Luca Ghilardi, University of Arizona; Andrea Scorsoglio, University of Arizona; Andrea D'Ambrosio, Sapienza Università di Roma; Roberto Furfaro, The University of Arizona; Fabio Curti, School of Aerospace Engineering, Sapienza University of Rome

As part of NASA's Vision for Space Exploration program, future human missions to the moon will require an increased automation level. In particular, it will be essential to perform safe landing autonomously in the presence of hazards. This work deals with an image-based hazard detection for both 3DOF (Degrees of Freedom) and 6DOF lunar landing. The proposed approach relies on the new deep learning semantic segmentation for image classification. Images are rendered using a detailed Digital Terrain Model (DTM) from which terrain features are extracted.

13:54 **AAS 21-253** **Uncertainty-Aware Deep Learning for Safe Landing Site Selection**

Katherine Skinner, University of Michigan; Kento Tomita, Georgia Institute of Technology; Koki Ho, Georgia Institute of Technology

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

14:06 **AAS 21-381** **The Application of Streaming Clustering to Spacecraft Identification and Tracking in Formation and Swarm Missions**

Jill Davis, Missouri University of Science and Technology; Henry Pernicka, Missouri University of Science and Technology

The continued development of small satellites has made them an increasingly viable mission alternative to traditional monolithic spacecraft. While Earth orbiting missions can rely on GNSS data for high-accuracy inertial and relative navigation, deep space missions will require new navigation techniques.This research presents a solution to the spacecraft identification and data association problem by using an unsupervised learning (clustering) architecture that classifies spacecraft from monocular camera images. Results show high levels of classification accuracy as well as the ability of the algorithm to adapt as the swarm configuration changes throughout the simulation.

14:18 **AAS 21-393** **Applications of Physics Informed Neural Networks for Gravity Field Modeling**

John Martin, University of Colorado Boulder; Hanspeter Schaub, University of Colorado

This paper introduces the use of Physics Informed Neural Networks (PINN) as a tool to unify flexible machine learning representations of the gravity field with the underlying analytic dynamics. By injecting the formal differential equations governing gravity into the neural network training process using automatic differentiation, this paper demonstrates that machine learning gravity models can be held to a higher level of rigor and accuracy than previously explored. Moreover this paper aims to demonstrate that PINNs can be a viable alternative to current analytic models both for applications in astrodynamics simulation and gravity field recovery.

14:30 **AAS 21-424** **Artificial Neural Network Based Prediction of Solar Array Degradation during Electric Orbit-Raising**

Tanzimul Farabi, Wichita State University; Atri Dutta, Wichita State University

This paper presents an artificial neural network based approach for predicting the power loss of all-electric satellites during low-thrust orbit-raising through the Van Allen radiation belts. The developed network can be beneficial in computing thrust availability of a satellite within low-thrust mission design tools. The network is trained on data generated using the AP/E9 models for radiation flux calculation and SPENVIS for power loss computation. Finally, the application of the network to a sequential low-thrust orbit-raising solver is demonstrated through numerical simulations for orbit-raising of telecommunication satellites starting from different geosynchronous transfer orbits.

14:42 **AAS 21-241** **Deep Learning HSGP4: Hyperparameters analysis**

Juan Félix San-Juan, University of La Rioja; Edna Viviana Segura Alvarado, University of La Rioja; Hans Carrillo, Universityof La Rioja; Rosario López, Universityof La Rioja; Iván Pérez, University of La Rioja; Montserrat San-Martín, University of Granada

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

Feb 2, 2021Virtual Room #1

11 - Low Thrust Trajectories II

Chair: Arnaud Boutonnet, European Space Agency / ESOC

10:30 **AAS 21-368** **Indirect Optimization for Low-Thrust Transfers with Earth-Shadow Eclipses**

Yang Wang, Politecnico di Milano; Francesco Topputo, Politecnico di Milano

An efficient indirect method is presented for low-thrust transfers in presence of Earth-shadow eclipses. The key feature of our method is the capability to offer accurate Jacobian of problem functions with respect to all decision variables, which is pivotal for robust convergence. Particular attention is paid to handling the discontinuity conduced by Earth-shadow eclipses. The state transition matrix at shadow entrance and exit is compensated using calculus of variations. A systematic framework for solving both time-optimal and fuel-optimal problems is established. The GTO to GEO transfers transfers are simulated to illustrate the effectiveness and efficiency of the method developed.

10:42 **AAS 21-369** **A new methodology for the solution to the stiffness problem applied to low-thrust trajectory optimisation in terms of orbital elements using the Differential Dynamic Programming**

Marco Nugnes, Politecnico di Milano; Camilla Colombo, Politecnico di Milano

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

10:54 **AAS 21-374** **Low-Thrust Trajectory Optimization Using the Kustaanheimo-Stiefel Transformation**

Kevin Tracy, Carnegie Mellon University; Zachary Manchester, Carnegie Mellon University

We present a novel trajectory optimization formulation for the low thrust orbital transfer problem that utilizes the Kustaanheimo-Stiefel transformation. For the unperturbed case, this transformation maps the nonlinear three-dimensional two-body dynamics to a four-dimensional linear harmonic oscillator. These new dynamics, even when perturbed, are significantly more linear than alternative state representations, and therefore a better candidate for trajectory optimization. By formulating a low thrust trajectory optimization problem with this model, a thrust plan can be solved for without an initial guess, and with fewer knot points than alternative state representations.

11:06 **AAS 21-384** **Low-thrust Transfer Trajectories to Earth-Moon Near Rectilinear Halo Orbits**

Emmanuel Blazquez, ISAE-SUPAERO; Alberto Fossà, Institut Supérieur de l'Aéronautique et de l'Espace (ISAE-SUPAERO); Tom Semblanet, ISAE-SUPAERO; Stéphanie Lizy-Destrez

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

11:18 **AAS 21-385** **Comparison of Costate Initialization Techniques For Fuel-Optimal Low-Thrust Trajectory Design**

Praveen Jawaharlal Ayyanathan, Auburn University; Ehsan Taheri, Auburn University

In this paper, two methodologies are investigated for generating missing initial costate values of boundary-value problems associated with fuel-optimal low-thrust trajectories. Solving the resulting boundary-value problems can become quite challenging due to 1) the presence of complex, non-smooth, bang-off-bang control structures, 2) small domain of convergence, and 3) lack of information about the value of missing costates. For three-dimensional fuel-optimal problems, the standard method of ``random initialization" is compared against a method in which the missing initial costates are constrained to lie on a unit 8-dimensional hyper-sphere. The results will be summarized for multi-revolution, fuel-optimal, low-thrust trajectories.

11:30 **AAS 21-388** **Hybrid Evolutionary-Indirect Multiple-Gravity-Assist Low-Thrust Interplanetary Trajectory Design**

Nicholas Nurre, Auburn University; Ehsan Taheri, Auburn University

In this work, an enhanced indirect optimization method is implemented as the inner-level solver within a hybrid dual-level algorithm. The input to the algorithm is a user-defined sequence of planets. The outer-level of the algorithm set the bounds for the design variables automatically and uses a global search algorithm (particle swarm optimization (PSO)) to generate problem boundary and gravity-assist parameters. The inner-level solver finds a fuel-optimal trajectory for each segment of the trajectory by solving a two-point boundary-value problem. The algorithm is capable of finding candidate optimal trajectories for interplanetary missions with forced coast arcs prior and post gravity-assist maneuvers.

11:42 **AAS 21-422** **Reachable set of low delta-v trajectories following a gravity-assist flyby**
Chun-Yi Wu, University of Texas at Austin; Ryan Russell, The University of Texas at Austin

Icy moons flyby tours are challenging to design due to the extraordinarily large search space. State-of-the-practice approaches rely on discretized grid searches over a reduced domain, and often waste computation on solutions with excessively high delta-v. A new method is proposed that (a) considers the full domain of reachable bodies and transfer types (VILT, resonant, non-resonant, even- and odd-Npi), (b) finds interpolatable families of solutions when degrees of freedom are available, and (c) structures the search to only find solutions within a delta-v threshold. This new approach is designed to inform an outer loop pathfinding scheme.

Feb 2, 2021Virtual Room #2

12 - Trajectory Design I

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

10:30 **AAS 21-221** **Invariant Funnels for Resonant Landing Orbits**
Jared Blanchard, Stanford University

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

10:42 **AAS 21-232** **Expected Thrust Fraction: Resilient Trajectory Design Applied to the Earth Return Orbiter**
Ari Rubinsztejn, University of Alabama; Rohan Sood, The University of Alabama; Frank Laipert, Jet Propulsion Laboratory

Electric propulsion is an enabling technology for NASA's Mars Sample Return mission. Unfortunately, electric propulsion makes spacecraft susceptible to missed thrust events. This paper investigates the application of expected thrust fraction to the Earth Return Orbiter's outbound Earth-to-Mars trajectory. Through the use of expected thrust fraction, a trajectory with a baseline 65.4% success rate is improved to an 86.6% success rate at the cost of only 12 kgs of delivered mass. Additionally, when expected thrust fraction is used in conjunction with other missed thrust event mitigation techniques, a 96.0% success rate is achieved.

10:54 **AAS 21-251** **Mission Analysis and Design of VMMO: The Volatile Mineralogy Mapping Orbiter**
Nicola Baresi, University of Surrey; Harry Holt, Surrey Space Centre; Nicolò Bernardinin; Xiaoyu Fu, University of Surrey; Mansur Tisaev; Yang Gao; Christopher Bridges; Andrea

Lucca Fabris; Roberto Armellin, ISAE-SUPAERO; Piotr Murzionak, MPB Communications; Roman Kruzelecky, MPB Communications

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

11:06 AAS 21-257 Functional Interpolation Method to Compute Period Orbits in the Circular Restricted Three-Body Problem

Hunter Johnston, Texas A&M University; Martin Wen-Yu Lo, Jet Propulsion Laboratory; Daniele Mortari, Texas A&M University

Computing Halo orbits, finding nonlinear periodic orbits in general, has become an important part of modern mission design. In this paper, we introduce a novel, simple, and efficient method for finding periodic orbits by analytically embedding the boundary-conditions using the Theory of Functional Connections.

11:18 AAS 21-274 Analytical Partial Derivatives of the Q-Law Guidance Algorithm

Jackson Shannon, University of Maryland; Donald Ellison, NASA Goddard Space Flight Center; Christine Hartzell

One method of producing low-thrust trajectories is the closed-loop Q-Law guidance algorithm. This work wraps Q-Law inside a nonlinear programming problem to search for locally optimal gain combinations and enforce nonlinear constraints on the initial state. Gradient-based trajectory optimization has been shown to benefit greatly when analytical partial derivatives are supplied to the optimizer. This paper presents the Q-Law optimization problem setup and derives the Q-Law thrust vector partial derivatives for the State Transition Matrix required by standard nonlinear optimization software.

11:30 AAS 21-334 I'll have the Porter: Interactively Visualizing the Results of Statistical Maneuver Analysis

Rohan Patel, California State Polytechnic University, Pomona; Jimmy Moore, University of Utah, School of Computing; Jeffrey Stuart, Jet Propulsion Laboratory; Sonia Hernandez, Jet Propulsion Laboratory; Emine Basak Alper Ramaswamy, NASA Jet Propulsion Laboratory

Statistical maneuver analysis is a key part of mission design and navigation, ensuring adequate margins on propellant and mission safety. Maneuver plans are validated through the use of Monte Carlo analysis simulating a variety of error sources and outputting a large quantity of data. We are developing a visual interface, Porter, focused on providing mission analysts the ability to probe the detailed results of a single Monte Carlo run. We discuss the development and core features of the Porter interface, detailing the design decisions both inthe user-oriented interface as well as the back-end data organization for the raw outputs.

11:42 **AAS 21-405** **Robust Multi-body Slewing Trajectories via Unscented Optimal Control**

Brian Bishop, Air Force Institute of Technology; Richard Cobb, Air Force Institute of Technology; Costantinos Zagaris, Air Force Institute of Technology

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

11:54 **AAS 21-234** **Exploration of Deimos and Phobos leveraging resonant orbits.**

David Canales Garcia, Purdue University; Maaninee Gupta, Purdue University; Beom Park, Purdue; Kathleen C. Howell, Purdue University

While the interest in future missions devoted to Phobos and Deimos rises, missions that explore both moons are expensive in terms of maneuver capabilities due to the lack of low-energy transfers. The proposed approach in this investigation includes Mars-Deimos resonant orbits that offer repeated Deimos flybys as well as access to libration point orbits in the Phobos vicinity. A strategy to select the candidate orbits is discussed and associated costs are analyzed, both for impulsive and low-thrust engine models, within the context of the coupled spatial circular restricted three body problem, which are then validated into a higher-fidelity ephemeris model.

Feb 2, 2021Virtual Room #3

13 - Spacecraft Control I

Chair: Francesco Topputo, Politecnico di Milano

10:30 **AAS 21-210** **MODIFYING AND OPTIMIZING THE INVERSE OF THE FREQUENCY RESPONSE CIRCULANT MATRIX AS AN ITERATIVE LEARNING CONTROL LAW**

Shuo Liu, Columbia University; Richard Longman, Columbia University

Feedback control systems do not do what you ask. Bandwidth tells what commands can be handled. Iterative Learning Control (ILC) seeks to perform high precision motions along a desired path for all frequencies after a few learning iterations. Use in spacecraft include performing highly accurate sensor scanning. ILC is finite time and therefore has initial transients. The purpose of this paper is to create a method of designing ILC compensators based on steady state frequency response, and have the ILC converge to zero error in spite of transients and bandwidth. A method of doing this is demonstrated with good performance.

10:42 **AAS 21-239** **Iterative Learning Control Inverse Problem Using Harmonic Frequency Filters**

Jer-Nan Juang, National Cheng Kung Univ; Richard Longman, Columbia University

Basic learning laws with the design of a filter are summarized and their input convergence conditions are described. This paper presents a cliff harmonic-frequency filter with a frequency cutoff and a weighted harmonic-frequency filter with frequency weighting for iterative learning control inverse problem. Filter matrices based on the state-space modelof a finite-difference digital filter are derived for Matlab's and Gustafsson's forward and backward filtering which are commonly called filtfilt methods. Furthermore, filter matrices for Matlab's and Gustafsson's filtfilts are revised to make the input convergence matrix to be monodically stable.

10:54 **AAS 21-272** **Identification of the Dynamics in the Singular Vectors of the System Toeplitz Matrix of Markov Parameters**

Jer-Nan Juang, National Cheng Kung Univ; Richard Longman, Columbia University

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

11:06 **AAS 21-278** **DESIGN TRADEOFFS USING SECOND ORDER REPETITIVE CONTROL TO REDUCE SENSITIVITY TO DISTURBANCE PERIOD**

Ayman Ismail, Columbia University; Richard Longman, Columbia University

Repetitive control is widely used for tracking a periodic command and/or eliminating a periodic disturbance of known period. Two issues can be encountered in applications: disturbance period is not known to high precision or is subject to fluctuations from random unmodeled effects. Second order repetitive control is developed as a method to widen notches and make the performance less sensitive to accurate knowledge or fluctuations in the period. To obtain best performance, tradeoffs related to error produced at addressed and intermediate frequencies must be made during design. This paper analyzes these tradeoffs and offers approaches to intelligently address each tradeoff.

11:18 **AAS 21-279** **Controller Design for Launch Vehicle with Internal Torque**

Ryan Kinzie, Embry-Riddle Aeronautical University; Dongeun Seo, Embry-Riddle Aeronautical University

This paper seeks to create a robust linear controller to compensate for a torque that is generated internally on a launch vehicle due to its engine design. A mathematical model of the internal torques of a general engine along with the torque's coupled nature to the throttle setting of the engine will be created and then analyzed in a six degree-of-freedom rigid-body modelof the launch vehicle. Modern control methods will then be utilized to generate a robust quaternion-based linear-quadratic regulator control algorithm, which is expected to be able to sufficiently compensate for the vehicle's internal torque and coupled forces.

11:30 **AAS 21-263** **Reduced Control Authority in a Dispersed Satellite Formation Antenna Array**

Mason Nixon, Leidos Inc. / University of Alabama in Huntsville Department of Electrical Engineering; Yuri Shtessel, University of Alabama in Huntsville Department of Electrical Engineering

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

11:42 AAS 21-390 Lyapunov-Based Control of Kinematically Coupled Close-Proximity Spacecraft Feature Point Dynamics

Eric Butcher, University of Arizona; Chad Wenn, University of Arizona

A nonlinear Lyapunov-based strategy for the 6-DOF control of kinematically coupled close-proximity spacecraft feature point dynamics is presented in which the feature point is an off-center-of-mass point of interest such as a docking port. The relative dynamics of the spacecraft centers-of-mass are described by the Hill-Clohessy-Wiltshire equations or other standard equations of relative motion, while additional terms account for the kinematic orbit/attitude coupling. Either global or almost global asymptotic stability is achieved depending on the attitude-dependent part of the control law. Monte Carlo simuluations demonstrate the success of the proposed technique.

11:54 AAS 21-255 A Near-Optimal Attitude Control for an Earth Imaging Satellite

Giovanni Lavezzi, South Dakota State University; Marco Ciarcia, South Dakota State University

This paper describes a near-optimal attitude control strategy for an Earth observation satellite. The proposed approach combines a direct method, the Inverse Dynamics in the Virtual Domain, and a nonlinear programming solver, the Sequential Gradient-Restoration Algorithm, for the fast calculation of the solution trajectory, enabling a closed-loop implementation. Optimality and pointing accuracy are assessed for several target acquisitions and tracking maneuvers performed in a high-fidelity simulation environment. Both minimum time and minimum control energy criteria are considered. Comparison against conventional attitude controllers, a quaternion feedback PD controller and a LQR, is also provided.

Feb 2, 2021Virtual Room #4

14 - Cislunar Space Situational Awareness

Chair: Brandon Jones, The University of Texas at Austin

10:30 AAS 21-450 Ground-Based Navigation Trades for Operations in Gateway's Near Rectilinear Halo Orbit

Matthew Bolliger, Advanced Space; Michael Thompson, Advanced Space; Nathan (Parrish) Ré, Advanced Space, LLC; Diane Davis, a.i. solutions, Inc.

This paper presents an analysis of ground-based tracking during operations in a 9:2 synodic-resonant Earth-Moon L2 southern NRHO. The performance of different tracking configurations is compared in terms of the annual orbit maintenance ?V, state uncertainties, state errors, and filter reliability.

Tracking configurations are parameterized based on track durations, locations within the NRHO, and number of tracks per revolution. Monte Carlo analysis with simulated observations is performed on each of 44 tracking configurations. Different filter setups are leveraged to identify outliers. The resulting filter solutions are compared to a notional reference requirement of 10 km, 10 cm/s 3? state uncertainty.

10:42 AAS 21-225 Assessing Observer Location Schemes for Cis-Lunar Space Domain Awareness

Michael Rosenof, Air Force Institute of Technology; Bryan Little, Air Force Institute of Technology

With renewed worldwide interest in cis-lunar space, the need for reliable domain awareness in that extended region of space is clear. This investigation quantifies the suitability of several possible stations for observer satellites in cis-lunar space by calculating the specific irradiance each would observe as they track satellites in various realistic lunar free-return trajectories across a decade. Early indications are that the combination of stations resulting in the best overall observation op-portunities is a single satellite orbiting L4 or L5, and a single satellite in low lunar orbit out of the plane of the Moon's orbit.

10:54 AAS 21-290 Cislunar Space Situational Awareness

Carolin Frueh, Purdue University; Kathleen C. Howell, Purdue University; Kyle DeMars, Texas A&M University

Classically, space situational awareness and space traffic management focuses on the near earth region, which is highly populated by satellites and space debris objects. With the expansion of space fairing further in the cislunar space, the problems of space situational awareness arises anew in regions fa away from the near earth realm. This paper investigates the conditions for successfulSpace Situational Awareness and Space Traffic Management in the Cislunar region by drawing direct comparison to the known challenges and solutions inthe near-Earth realm, highlighting similarities and differences and their implication on Space Traffic Management engineering solutions.

11:18 AAS 21-406 Observability Metrics for Space-Based Cislunar Domain Awareness

Erin Fowler, University of Maryland College Park; Derek Paley, University of Maryland College Park; Stella Hurtt, University of Maryland College Park

We present a dynamic simulation framework of the cislunar environment for use in numerical analysis of various pairings of resident space objects and observer satellites intended for cislunar space domain awareness. The paper's contributions include analysis of orbit families for the mission of space-based cislunar domain awareness and a set of metrics that can be used to inform the specific orbit parameterization for cislunar SDA constellation design. The empirical observability Gramian, along with several heuristic metrics, is computed for observations of satellites on trajectories in the Earth-Moon system to assess their degree of observability for a given observer-target orbit pair.

15 Dynamical System Theory I

Chair: Donghoon Kim, University of Cincinnati

10:30 **AAS 21-270** **Quasi-Periodic Orbits in the Sun-Earth-Moon Bicircular Restricted Four-Body Problem**

Brian McCarthy, Purdue University; Kathleen C. Howell, Purdue University

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

10:42 **AAS 21-307** **DESIGN OF SOLAR SAILING IN SUN-EARTH-MOON SYSTEM AND TRANSFER TO INTERPLANETARY REGION**

Toshihiro Chujo, Tokyo Institute of Technology; Yuki Takao, Japan Aerospace Exploration Agency

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

10:54 **AAS 21-310** **On the use of zero-momentum surfaces to identify transport opportunities to planar Lyapunov orbits**

Roshan Thomas Eapen, Texas A&M University; Kathleen C. Howell, Purdue University; Kyle T. Alfriend, Texas A&M University

Transfer trajectory design in the restricted three-body problem is largely dependent on the topology of the invariant manifolds. In this paper, the behavior of such manifolds are studied through the use of a Poincaré map generated from a zero-momentum subspace of the third-body motion. Such maps characterize the regions of allowed motions of the invariant manifolds to occupy the space bounded by quasi-periodic orbits. The dynamical structures arising from these zero-momentum surfaces are instrumentalin identifying transport opportunities to planar Lyapunov orbits and give an upper bound on the manifold insertion angle for tangential transfers.

11:06 **AAS 21-317** **Theory of low-energy transit orbits in the periodically-perturbed restricted three-body problem**

Joshua Fitzgerald, Virginia Tech; Shane Ross

In the circular restricted three-body problem, low-energy transit orbits are revealed by linearizing the governing differential equations about the Lagrange points. This procedure fails when time-periodic perturbations are considered, such as perturbation of the sun (ie., the bicircular problem) or orbital eccentricity of the primaries. For this case, the Lagrange point is replaced by a periodic orbit, viewed as an index-1 saddle fixed point of a symplectic map. In analogy with the geometry about an index-1 saddle equilibrium point, transit and non-transit orbits are identified in the saddle canonical plane. Furthermore, the linearized symplectic map admits a conserved quadratic Hamiltonian.

11:18 **AAS 21-343** **Defining the Fundamental Frequencies of Quasi-Periodic Invariant Tori**

Luke Peterson, University of Colorado Boulder; Daniel Scheeres, University of Colorado Boulder

Quasi-periodic orbits are higher-dimensional solutions of Hamiltonian dynamical systems that lie on the surface of invariant tori. Quasi-periodic motion on the torus is fully described by the frequencies of motion on the torus; however, any unimodular mapping of the frequency vector offers an equivalent representation. This work presents an approach to uniquely define the frequencies of a quasi-periodic invariant torus. The group-theoretic approach exploits the action of unimodular matrices on the set of frequencies so that the fundamental frequencies are closest to resonance. We include examples applied to center manifolds emanating off of periodic orbits in the Hill three-body problem.

11:30 **AAS 21-349** **Using GPUs and the Parameterization Method for Rapid Search and Refinement of Connections between Tori in Periodically Perturbed Planar Circular Restricted 3-Body Problems**

Bhanu Kumar, Georgia Institute of Technology; Rodney L. Anderson, Jet Propulsion Laboratory/Caltech; Rafael de la Llave, Georgia Institute of Technology

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

11:42 **AAS 21-363** **HYPERCOMPLEX UNIVERSAL VARIABLES APPROACH FOR THE STATE TRANSITION MATRIX IN THE GENERAL KEPLERIAN RELATIVE ORBITAL MOTION**

Daniel Condurache, Technical University of Iasi; Vladimir Martinusi, Technion - Israel Institute of Technology

The paper presents a unified approach to the explicit computation of the state transition matrix (STM) associated to the relative orbital motion in Keplerian arbitrary orbits. The use of the hypercomplex universal variables allows the unified formulation of the STM, regardless the elliptic, parabolic or hyperbolic nature of their inertial trajectories. The universal variables approach offers a parameterization of the geodesics in the constant curvature phase space on which the inertial motion takes place. The parameterization is made with the help of the generalized trigonometric functions in a space of constant mean curvature.

11:54 **AAS 21-360** **Navigating Low-Energy Trajectories to Land on the Surface of Europa**

Sonia Hernandez, Jet Propulsion Laboratory; Rodney L. Anderson, Jet Propulsion

Laboratory/Caltech; Yu Takahashi, Jet Propulsion Laboratory; Duane Roth, Jet Propulsion Laboratory; Tim McElrath, JPL/Caltech*

Navigation strategies typically use linearized techniques to predict maneuver statistics and perform orbit determination. A linearized approach works well for high-energy trajectories, since the “true” trajectory is well approximated by a linearized trajectory when propagated for short periods of time. On the other hand, low-energy trajectories, such as those needed to explore planetary moons, are highly nonlinear and sensitive to small perturbations; thus the typical linearized navigation techniques are no longer valid. In this paper we explore different approaches to performing maneuver design for low-energy trajectories, with an emphasis on the approach phase of a Europa lander concept mission.

Feb 2, 2021Virtual Room #1

16 - Trajectory Design II

Chair: Powtawche Valerino, NASA Marshall Space Flight Center

13:30 **AAS 21-252** **Escape Trajectories from Lagrangian Points with Electric Propulsion**
Luigi Mascolo, Politecnico di Torino; Lorenzo Casalino, Politecnico di Torino - DIMEAS

An indirect method to determine optimal low-thrust trajectories for the escape from Earth’s sphere of influence, starting from L2 and NRHO, is developed. The highly chaotic and non-linear dynamics of motion close to Lagrangian points challenges the remarkable precision of the indirect method: new approaches and improvements to handling these numerical problems are identified and implemented, as a multifield and multi-shooting method in which the trajectory splits at the high-velocity gradient points. The dynamic model considers 4-body gravitation, JPL' ephemeris, and may include spherical harmonic models for Earth and Moon; solar radiation pressure is also considered.

13:42 **AAS 21-291** **Multidisciplinary System Design Optimization of Lunar Surface Access from Cislunar Orbit via Surrogate-Assisted Evolutionary Algorithms Using Highly-Parallel GPU Architecture**
Kyuto Furutachi, Kyushu University; Hideaki Ogawa, Kyushu University; Satoshi Ueda, Japan Aerospace Exploration Agency

Global optimization draws increasing attention with the advancement of space missions and increasing complexity of spacecraft systems. A Multidisciplinary System Design Optimization (MSDO) framework has been developed for the lunar surface access mission consisting of NRHO-LLO transfer and lunar landing phases by performing orbit propagation and surrogate modeling on GPU (graphics processing unit) cores in conjunction with surrogate-assisted evolutionary algorithms. A distinct Pareto optimal front has resulted from a large-scale MSDO study exploiting a highly parallelized architecture enabled by GPUs, which would otherwise be prohibitive for traditional approaches using CPUs. The results have been scrutinized and a global sensitivity analysis has been conducted to gain insights into the key design factors and interactions between subsystems and orbital transfer.

13:54 **AAS 21-320** **Global Trajectory Optimization of Earth-NRHO Transfer Using Weak Stability Boundary Via GPU-Based Super-Parallelization**

Satoshi Ueda, Japan Aerospace Exploration Agency; Hideaki Ogawa, Kyushu University

This paper presents a global trajectory optimization framework via a multi-fidelity approach that utilizes a GPU for low-fidelity initial solution search and a CPU to determine high-fidelity feasible solutions. A multi-fidelity approach is proposed to enable global trajectory optimization of Earth-NRHO transfer. The present study employs a weak stability boundary transfer that utilizes solar tidal force for velocity increment saving. The knowledge and insights are summarized for the resultant global structure of feasible solutions, while verifying the capability and effectiveness of the global design framework enabled by a GPU-based highly-parallel architecture.

14:06 **AAS 21-345** **Recovery Trajectories for Inadvertent Departures from an NRHO**

Emily Zimovan-Spreen, Purdue University; Diane Davis, a.i. solutions, Inc.; Kathleen C. Howell, Purdue University

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

14:30 **AAS 21-392** **EFFECTS OF V-INFINITY LEVERAGING WITH LUNAR-EARTH GRAVITY ASSIST ON INTERPLANETARY TRAJECTORI ES**

Giuliana Elena Miceli, ISAE SUPAERO; Stefano Campagnola, Jet Propulsion Laboratory

This works evaluates the effects of Lunar-Earth Gravity Assist on mission design and Δv budget, using V-infinity leveraging. The Earth is often exploited for flybys during interplanetary trajectories. The use of the Moon, in combination with the Earth, provides additional deviation of the hyperbolic excess velocity with respect to the Earth and modifies its magnitude, increasing the overall flyby performance. The Lunar-Earth Gravity Assist has been evaluated for external leveraging, both for Short and Long transfers. Asample mission to Jupiter is showcased and results suggest that the Moon effect during the flyby reduces the leveraging Δv by 5.3%.

14:42 **AAS 21-403** **Periapsis Targeting with Weak Stability Boundary Transfers for Orbiting around Planetary Moons**

Yuri Shimane, Georgia Institute of Technology

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

14:54 **AAS 21-452** **Lunar Impact Probability for Spacecraft in Near Rectilinear Halo Orbits**
Diane Davis, a.i. solutions, Inc.; Rolfe Power, Purdue University; Kathleen C. Howell, Purdue University; Jeffrey Gutkowski

Near Rectilinear Halo Orbits (NRHOs) near the Moon are of recent interest for missions including Gateway and CAPSTONE. To address planetary protection considerations during long-term NRHO operations, the probability of impact on the lunar surface following a wide range of ?*v* perturbations is assessed. The effects of disturbance distribution around the NRHO and the short-term destination of escaping particles are explored. The likelihoods of collision across the entire lunar surface and within sensitive polar regions are considered in both the Circular Restricted Three-Body model and in the higher-fidelity ephemeris force model.

Feb 2, 2021 Virtual Room #2

17 - Spacecraft Control II

Chair: Ossama Abdelkhalik, Iowa State University

13:30 **AAS 21-247** **Study on Autonomous Gravity-Assists with a Path Following Control**
Rodolfo Batista Negri, National Institute for Space Research; Antonio Fernando Bertachini Prado, INPE

An autonomous control of gravity-assist hyperbolic trajectories is studied. In order to do so, it is applied a path following control law that uses sliding mode control theory to guarantee robustness to bounded disturbances. Other advatange is that this path following is specially derived to maintain any Keplerian motion. The control strategy is tested in the Jovian system, with multiple flybys by all Galilean moons.

13:42 **AAS 21-262** **Adaptive control for proximity maneuvers around asteroids using Extreme Learning Machine-based gravity field estimation**
Andrea D'Ambrosio, Sapienza Università di Roma; Gabriele Conforti, School of Aerospace Engineering, Sapienza University of Rome; Ivan Agostinelli, School of Aerospace Engineering, Sapienza University of Rome; Fabio Curti, School of Aerospace Engineering, Sapienza University of Rome

Proximity operations around asteroids are challenging because of the difficulties in the real-time estimation of their gravity field. A direct adaptive control is employed to study proximity maneuvers around asteroids. The adaptive control law is directly adjusted to minimize the error between plant and reference trajectory outputs. The control law's gains are tuned to obtain the desired performances. Furthermore, to consider a fast and accurate estimation of the gravity, Extreme Learning Machine is exploited to map the position vector into the gravity vector in the asteroid body-fixed frame. Finally, all the framework is applied to proximity maneuvers around asteroid Gaspra

13:54 **AAS 21-294** **Robust Adaptive Control for Attitude Control of Spacecraft Formation Flying**
Soobin Jeon, Yonsei University, Korea; Hancheol Cho, Bradley University; Sang-Young Park, Yonsei University

A continuous adaptive sliding mode controller is proposed for precise attitude control of spacecraft formation flying. The time continuity of controlinput successfully eliminates chattering and achieves finite-time convergence in the presence of unknown bounded uncertainties. To automatically updates the control gain without prior knowledge of the disturbances, a simple adaptive law is developed. Numerical simulations are conducted for three types of attitude control problems and suggest the robustness and accuracy of the proposed controller while successfully compensating disturbances from uncertainties of the momentum of inertia and external environments.

14:06 AAS 21-319 Physics-Informed Neural Network Solutionof Hamilton-Jacobi-Bellman Equations for a Class of Space Optimal Control Problems

Roberto Furfaro, The University of Arizona; Andrea Scorsoglio, University of Arizona; Enrico Schiassi, University of Arizona

In this paper, finite and infinite horizon optimal control problems for general and space applications are solved via a dynamic programming approach using Physics-Informed Neural Networks (PINNs).

In particular, the arising Hamilton Jacobi Bellman partial differential equation, that guarantees a necessary and sufficient condition for the optimality and provides a closed loop solution, is solved via PINNs.

PINNs are particular neural networks where the training is regulated by the physics of the problem, modeled through differential equations.

14:18 AAS 21-355 Closed-Loop Optimal Control for Spacecraft Rendezvous and Proximity Operations Using Second-Order Cone Programming

Michael Devore, Barron Associates Inc; Richard Adams, Barron Associates Inc; Adam Reed, Barron Associates Inc; Alexander Lewis , San Diego State University; Ping Lu, San Diego State University

Autonomous guidance and control solutions for spacecraft rendezvous and proximity operations (RPO) must be robust to modeling uncertainties, unmodeled dynamics, errors in thruster output and alignment, sensor bias and noise, and environmental disturbances. An autonomous control system may also have to contend with emerging debris or other obstacles. This paper presents a closed-loop control approach based on second-order cone programming (SOCP) that supports continuous re-generation of a fuel-optimal control solution that satisfies inequality constraints as well as equality constraints on interior points and terminal conditions within a multi-phase mission.

14:30 AAS 21-391 Modeling and Control of an Electromagnetic Docking System for the SAS-SAT CubeSat Mission

Kyle Rankin, New Mexico State University; Hyeongjun Park, New Mexico State University; Steven Stochaj, New Mexico State University

The Satellite Alignment System SATellite (SAS-SAT) demonstrates a low-cost system to perform the final approach to docking between two CubeSats utilizing electromagnets. This paper shows the development of the dynamics model. Additionally, this paper goes into a detailed analysis of the controlsystem's required, including PID, LQR, and MPC controllers. This paper presents an analysis of the viability of such a system looking at variables such as the required magnet size, and the range at which the magnetic docking system becomes viable. Finally, this paper will estimate the sizing of the electromagnets, and the attitude control system.

14:42 **AAS 21-412** **Attitude and Orbit Control System for a High-Resolution FIREFLY Satellite**
Karthic Balasubramanian, Syzygy Space Technologies (Pixxel Space Technologies Inc); Piruthvi Chendur Palanisamy, Syzygy Space Technologies PvtLtd (Pixxel Space)

High resolution earth imaging satellites have traditionally been large satellites. The companies like Pixxel are achieving high resolution requirement with a microsatellite as small as 30 kilogram in size. The authors explore the development of high precision Attitude and Orbit Control System (AOCS) for such a Low Earth Orbit (LEO) microsatellite mission. The satellite will be launched by Falcon-9 and it is positioned in a circular Sun-Synchronous Polar Orbit of altitude 550km above earth's surface by an Orbit Transfer Vehicle (OTV). The satellite is to be deployed with an orbit inclination of 97.5 deg.

14:54 **AAS 21-418** **Three-Axis Reaction Wheel Desaturation using Two-Axis Gimbaled Thruster on a non-Diagonal Inertia Satellite**
Carlos Montalvo; William Sherman, University of South Alabama

For institutions with satellite missions limited by budget and dimensional constraints, having redundant control authority over all three rotational axes might prove challenging by only having means of secondary attitude control actuation on two axes. This develops an inherent problem when reaction wheel saturation occurs. A control system is developed in this paper that allows for full three-axis desaturation of a spacecraft's reaction wheels via a gimbaled thruster with only two axes of rotation. This is accomplished by utilizing the property that a non-diagonal inertia matrix will cause rotation in one axis to transfer momentum to another axis. The full manuscript will include full control law derivation.

Feb 2, 2021Virtual Room #3

18 - Space Object Characterization and Independent Attitude Determination

Chair: Piyush Mehta, West Virginia University

13:30 **AAS 21-246** **Multi-Scale Convolutional Neural Networks for Inference of Space Object Attitude Status from Detrended Geostationary Light Curves**
Gregory Badura, GTRI; Brian Gunter, Georgia Institute of Technology; Christopher Valenta, Georiga Tech Research Institute; Brian Shoffeitt, Georgia Tech Research Institute

Convolutional neural network architectures were utilized to classify simulated geo-stationary RSO light curves into one of three operational states: controlled, maneuvering, or tumbling. Two different architectures were trained on a dataset of full- and partial-night light curves: (1) a Multi-scale Convolutional Neural Network (MCNN), and (2) a deep Convolutional Neural Network (CNN). The MCNN incorporates frequency domain pre-processing and multi-scale feature extraction, allowing it to extract behaviors occurring on different timescales. Our results show that the MCNN does not out-perform the deep-CNN, suggesting that it is potentially better to utilize model architectures that fully automate the process of feature extraction.

13:54 **AAS 21-327** **Empirical Approaches to Ultra-Wide Angle Lens Calibration**
Sam Wishnek, CU Boulder; Marcus Holzinger, University of Colorado Boulder

Optical data pre-processing for space situational awareness requires lens calibration where the distortion induced by the optical system is accounted for in extracting the angular measurements of a target. Existing methods for image calibration attempt to fit the data to a function-based model. This approach does not perform well for lenses with a very large field of view or asymmetric distortions. Here is presented an algorithm for empirically calibrating night sky images taken with ultra-wide angle lenses in order to generate mappings between pixels and inertially registered line- of-sight beams better than existing functional methods.

14:06 AAS 21-323 Light-Robust Shape-from-Silhouette Algorithmfor Autonomous Optical Navigation to an Unknown Small Body

Saptarshi Bandyopadhyay, Jet Propulsion Laboratory, California Institute of Technology; Jacopo Villa, University of Colorado Boulder; Alan Osmundson, University of Southern California, ; Benjamin Hockman, Jet Propulsion Laboratory, California Institute of Technology; Benjamin Morrell, NASA Jet Propulsion Laboratory; Daniel Lubey, Jet Propulsion Laboratory, California Institute of Technology; Shyam Bhaskaran, Jet Propulsion Laboratory; David Bayard, Jet Propulsion Laboratory; Issa Nesnas, Jet Propulsion Laboratory, California Institute of Technology

We present an advanced Shape-from-Silhouette (SFS) algorithm, which is robust to illumination conditions and non-zero sun phase. SFS is an important step in the optical navigation pipeline for an autonomous small spacecraft to approach an unknown small body.
The algorithm estimates the rotation-axis pole and 3D shape (visual hull) of the small body using only the lit pixels within the silhouette of the small body, rotation rate, and spacecraft-target relative poses from orbit determination.
We present detailed numerical simulations and multiple sensitivity analyses to demonstrate the effectiveness of our proposed SFS algorithm.

14:18 AAS 21-433 Modeling and Simulation of Rotary Sloshing in Launch Vehicles

Jeb Orr, Mclaurin Aerospace

Recent experience has reemphasized the risk of rotary sloshing limit cycles in launch vehicle propellant tanks. A detailed analysis of mechanical analogs for the simulation of nonlinear fluid dynamic coupling in axisymmetric containers is presented. A novel formulation is derived that is easily coded for simulation and incorporates damping asymmetry for tanks with ring baffles. Theoretical and simulation results are compared with historical test data. High-fidelity Monte Carlo simulation of a liquid-propellant vehicle is used to compare the present approach with traditional mechanical models of propellant slosh.

14:30 AAS 21-283 Real-Time, Flight-Ready, Non-Cooperative Spacecraft Pose Estimation Using Monocular Imagery

Kevin Black, Texas Spacecraft Laboratory; Shrivu Shankar, Texas Spacecraft Laboratory; Daniel Fonseka, Texas Spacecraft Laboratory; Jacob Deutsch, Texas Spacecraft Laboratory; Abhimanyu Dhir, Texas Spacecraft Laboratory; Maruthi R. Akella, The University of Texas at Austin

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

Feb 2, 2021Virtual Room #4

19 - Asteroids II & Mars

Chair: Anil Rao, University of Florida

13:30 **AAS 21-245** **Flexible and single-impulse transfers for asteroid retrieval using the invariant manifolds of the Circular-Restricted Three-body Problem**

Jack Tyler, University of Southampton; Alexander Wittig, University of Southampton

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

13:42 **AAS 21-299** **Deimos Flyby Observation Analysis using Resonant Flybys for the MMX Mission**

Ferran Gonzalez-Franquesa, SOKENDAI, The Graduate University for Advanced Studies; Naoya Ozaki, ISAS, JAXA; Yasuhiro Kawakatsu, JAXA / ISAS

JAXA's next flagship mission Martian Moons eXploration (MMX) will visit Phobos and Deimos. The mission aims to provide answers on the formation and evolution of the moons and, by extension, the the inner Solar System. Due to the nature of the Mars-Deimos system and mission constraints, the exploration of Deimos will be carried out via multiple resonant flybys. This approach allows the MMX probe to perform close-up observations of largely unexplored regions of the moon under desired solar illumination conditions, maximizing the scientific output.

13:54 **AAS 21-304** **Observability-Aware Trajectory Optimization for Small-body Gravity Estimation**

Masahiro Fujiwara, The University of Tokyo; Ryu Funase, The University of Tokyo

In small-body explorations, gravity estimation is a critical task to design trajectories for main operations and identify some characteristics of the target body. The gravity field can be recovered by tracking perturbed spacecraft'strajectory around the body. For more effective gravity estimation, this research proposes the sampling-based optimization method to find the trajectory where a trace of the gravity coefficients' covariance matrix or a trace of the inverse of observability gramian is the smallest. Numerical simulations show the optimal trajectories are different between the covariance matrix and observability gramian.

14:06 **AAS 21-336** **Comparing Optical Tracking Techniques in Distributed Asteroid Orbiter Missions Using Ray-Tracing**

Kaitlin Dennison, Stanford University Space Rendezvous Laboratory; Simone D'Amico, Stanford University

Keypoint descriptors are compared to a characteristic-specific landmark descriptor (craters) for optical tracking within a monolithic and distributed space system orbiting an asteroid. Additionally, a novel method to validate correlations between any landmark descriptors using ray-tracing is developed. Optical tracking methods are evaluated in simulation to identify tracking limitations. Simulated test cases are validated using the ray-trace matching technique. Ray-trace matching and optical tracking are further validated using images from a robotic testbed and real images from NEAR Shoemaker. Craters are shown to be at least comparable to keypoint descriptors. Ray-trace matching shows great potential for optical tracking validation.

14:18 AAS 21-358 Station Keeping of Satellites in Areostationary Mars Orbit using Model Predictive Control

Robert Halverson, Department of Aerospace Engineering and Mechanics, University of Minnesota - Twin Cities; Avishai Weiss, MERL; Ryan Caverly, University of Minnesota

In this paper, a model predictive control (MPC) station keeping policy is applied to a spacecraft orbiting Mars in an areostationary orbit. A high-fidelity orbital model is presented that considers the significant orbital perturbations caused by Mars' non-Keplerian gravitational potential, the presence of the Sun and Mars' moons, and solar radiation pressure. An MPC policy is implemented with the objective of minimizing fuel consumption while remaining within a prescribed station keeping window. Simulation results at a stable longitude demonstrate the MPC policy meets the defined objectives, while providing a benchmark for the annual fuel required for Martian station keeping.

14:30 AAS 21-444 GNC of a Tethered Robotic Explorer for Accessing Cliffs, Canyons, and Craters on the surface of Mars

Jekan Thangavelautham, University of Arizona

14:42 AAS 21-445 Advancing Asteroid Surface Mobility Using Machine Learning and the SPIKE Spacecraft Concept

Jekan Thangavelautham, University of Arizona

Feb 2, 2021 Virtual Room #5

20 - Space Robotics and Autonomous Operation & Lunar

Chair: Manoranjan Majji, Texas A&M University, College Station

13:30 AAS 21-285 DYNAMIC MODELING AND CONTROL FOR A TETHER-DRIVEN MULTI - MANIPULATORS SYSTEM CAPTURING A TUMBLING TARGET

Qiming Luo, School of Aerospace Engineering,Beijing Institute of Technology; Quan Hu, School of Aerospace Engineering, Beijing Institute of Technology

A novel mechanism is proposed in this work for tumbling target capture — tether-driven multi-manipulators system. It is consisted of four 2-DOFs manipulators, and a tether connecting the tips of the manipulators. The tether length can be controlled by a motor at one manipulator's tip, so the configuration and motion of the system are controlled by the tether, as well as the joint motor in the manipulators. We investigate the dynamic modeling and trajectory tracking control for this tether-driven multi-manipulators system.Numerical simulations demonstrates the proposed mechanism is effective in capturing a non-cooperative target.

13:42 AAS 21-337 Sustained Low-Altitude Lunar Orbital Mission (SLALOM) Navigation Concept

Jeff Parker, Advanced Space, LLC; James Thomas, Advanced Space; Sai Chikine, Advanced Space; Charles Cain, Advanced Space; Matthew Bolliger, Advanced Space

This paper describes the autonomous navigation system that is being developed to demonstrate the autonomous navigation of a spacecraft traversing an incredibly low-altitude lunar orbit. The Sustained Low-Altitude Lunar Orbital Mission (SLALOM) is a proposed mission concept that would place a spacecraft into an orbit with a mean altitude of < 10 km and maintain it there for multiple months. The autonomous navigation system includes a collection of onboard orbit determination filters and an autonomous maneuver design system, each of which must operate without any ground inputs for sustained periods of time, through multiple maneuvers.

13:54 AAS 21-401 Methods in Triangulation for Image-Based Terrain Relative Navigation

Kevin Kobylka, Rensselaer Polytechnic Institute; John Christian, Rensselaer Polytechnic Institute

Imagery obtained by a spacecraft in orbit around a celestial body can provide directional measurements from the spacecraft to multiple landmarks on the surface of the body. These measurements may be used to estimate the spacecraft location by triangulation. While the direct linear transform (DLT) method allows for a non-iterative solution for spacecraft localization, it creates a least squares problem with sometimes undesirable error characteristics. This work explores several solutions to the triangulation problem and evaluates their relative efficacy within the context of spacecraft terrain relative navigation (TRN).

14:06 AAS 21-284 LIBRATION REDUCTION DURING PARTIAL SATELLITE RETRIEVAL OF VERTICAL THREE-MASS TETHERED SYSTEMS

Derek Bourabah, University at Buffalo; Eleonora Botta, University at Buffalo

Tether retraction in a three-mass tethered satellite system is an unstable process in which libration angle increases over time. A simple control method is proposed to significantly reduce libration during a partial retraction maneuver. The proposed method introduces short periods of extension during retrieval. Simulations with varying initial conditions and number of extension/retraction cycles show that the controlalgorithm is effective. It is found that performing the maneuver too many times will diminish the efficiency. Ideally, the proposed methodology is applied to the two tethers, but if only one tether is to be controlled, the lower tether should be maneuvered.

14:18 AAS 21-333 Design and Analysis of Deployment Mechanics for a Self-Folding, Spiral Based Space-Borne Interferometer

Kanak Parmar, Auburn University; Manuel Indaco; Ryan Long; Will Taylor; Nathaneal Adkins; Deepika Singla; Russell Mailen; Davide Guzzetti, Auburn University

Ground observation of the Dark Ages signal is impeded by the Earth's atmosphere, which induces significant signal distortions at frequencies below 30 MHz. Compared to traditional methods, we propose a space-borne interferometer comprised of dipole antennas, embedded within a deployable, kilometer-size orbiting spiral in cislunar space. This structure is composed of shape memory polymer material marked by ink hinges that absorb solar radiation, triggering a temperature gradient that causes the material to fold. In this work, we initiated the design and analysis the spiral deployment mechanics and the resulting array performance to propose the appropriate space-borne interferometer architecture.

14:30 **AAS 21-435** **Slant Range Measurements for Lunar Terrain Relative Navigation**

Randall Christensen, Utah State University

14:42 **AAS 21-453** **Point Mascon Global Lunar Gravity Models**

Sean McArdle, University of Texas at Austin

Lunar gravitational models are generated using sets of point mass potentials fit to the recent, highly resolved GRGM1200A representation derived from GRAIL mission data. Point mass ensembles are highly parallelizable and can encode the gravitational potential and its gradients to an arbitrary order. A new model generation algorithm uses nonlinear optimization to assign point mass positions that best reproduce the gravitational field. The new technique generates models with improved numerical stability, memory cost, and evaluation runtime speed. A database of point mascon models is released, including driver routines that evaluate the gravitational potential gradients up to third order.

14:54 **AAS 21-425** **Nearly Constant-Time SLAM-based Terrain Relative Navigation for Landing on an Uncharted World**

Matthew Givens, University of Colorado Boulder; Jay McMahon, University of Colorado Boulder

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

Feb 3, 2021Virtual Room #1

21 - Trajectory Optimization

Chair: Sonia Hernandez, Jet Propulsion Laboratory

10:30 **AAS 21-207** **Quantum-inspired Diffusion Monte Carlo Optimization Algorithm applied to Space Trajectories**

Federico De Grossi, Sapienza University of Rome; Christian Circi, Sapienza University of Rome

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

10:42 **AAS 21-293** **Global Optimization of Manifold-Based Transfers to Halo and Butterfly Orbits Using Highly-Parallel GPU Architecture**

Yang Foo, Kyushu University; Hideaki Ogawa, Kyushu University; Satoshi Ueda, Japan Aerospace Exploration Agency; Mai Bando, Kyushu University

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

10:54 **AAS 21-297** **Optimal injection into Quasi-Satellite Orbits around Phobos: application to MMX mission**

Nicola Marmo, The Graduate University for Advanced Studies (SOKENDAI) - ISAS/JAXA; Diogene Alessandro Dei Tos, JAXA; Hitoshi Ikeda, Japan Aerospace Exploration Agency; Yasuhiro Kawakatsu, JAXA / ISAS

The Japan Aerospace Exploration Agency is aiming to launch in 2024 the Martian Moons eXploration mission. The main scientific objective is to survey the two Martian moons and to return a sample from the surface of Phobos. As nominal scientific orbits, several Quasi-Satellite Orbits around Phobos have been computed and adopted in consideration of the complex dynamical environment characteristic of the Mars--Phobos system. This paper explores the performance capability of a multi-impulsive control strategy to inject the MMX probe into a host of QSOs around Phobos, after a heliocentric journey from the Earth. A perturbation analysis in the vicinity of

11:06 **AAS 21-318** **Spacecraft Trajectory-Propulsion Co-optimization Using Enhanced Regularized Indirect Methods**

Vishala Arya, Texas A & M University; Ehsan Taheri, Auburn University; John L. Junkins, Texas A&M University

Application of idealized constant-specific-impulse, constant-thrust electric thruster performance models or curve-fitted polynomials is quite common. In this paper, a framework is developed for co-optimization of 1) spacecraft trajectory, 2) operations modes of multi-mode propulsion systems, and 3) solar array size. The selection of the most optimal operation modes is in accordance to

Pontryagin's minimum principle for solving a payload-mass-maximization problem. The novelty is enhanced by solving a mixed-integer featuring user-defined constraints on the maximum number of operating modes used along the trajectory. Utility of the framework is demonstrated through a multi-year trajectory from Earth to Gerasimenko using an SPT-140 thruster with 21 operating modes.

11:18 **AAS 21-404** **Optimal Maneuver Targeting Using State Transition Tensors with Variable Time-of-Flight**

Spencer Boone, University of Colorado Boulder; Jay McMahon, University of Colorado Boulder

This paper presents a methodology for expanding the higher-order state transition tensors (STTs) of a reference trajectory with respect to the final time over which the trajectory is propagated. Following this, a maneuver targeting and optimization scheme with a variable time-of-flight is developed using only the STTs of the reference trajectory. The algorithm is used to efficiently compute accurate and near-optimal stationkeeping maneuvers for a spacecraft operating in a halo orbit in the Earth-Moon system. The optimization scheme is computationally lightweight, and could be suitable for on-board use in highly nonlinear dynamical systems.

11:30 **AAS 21-407** **Optimized Jupiter Gravity Assists – Analytic Approximations**

Ralph McNutt, JHU Applied Physics Laboratory

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

11:42 **AAS 21-408** **Costate Transformation for Indirect Trajectory Optimization**

Ehsan Taheri, Auburn University; Vishala Arya, Texas A & M University; John L. Junkins, Texas A&M University

A methodology is proposed to establish costate transformation between any two sets of coordinates. It has utility for solving optimal control problems using indirect methods. The Jacobian of the nonlinear map between any two sets of coordinates/elements turns out to be the critical component in the costate vector transformation theory. Application of the proposed method and its utility are demonstrated through a number of time- and fuel-optimal trajectory optimization problems.

Feb 3, 2021 Virtual Room #2

22 - Formation Flying

Chair: Robert Melton, Pennsylvania State University

10:30 **AAS 21-282** **Spacecraft Close-Range Trajectory Planning via Convex Optimization with Guaranteed Convergence**

Guoxu Zhang, Beijing Institute of Technology; Changxuan Wen, Beijing Institute of Technology; Qiao Dong, Beijing Institute of Technology

A novel convexization method is proposed to solve both fuel-optimal and time-optimal spacecraft close-range trajectory planning problems. First, the nonlinear terms in dynamics are transformed into path constraints through the redefinition of variables. Then, the introduction of intermediate variables and convex-concave decomposition are adopted to handle path constraints. In this manner, the objective is linear after discretization, the equality constraints are affine, and the nonlinearity is concentrated in cone constraints and concave inequality constraints. Then, concave inequality constraints are linearized. Furthermore, a general sequential solution algorithm is proposed and the convergence of the algorithm can be proved.

10:42 **AAS 21-287** **DISTRIBUTED PATH PLANNING METHOD FOR LARGE-SCALE SWARM SAFE MIGRATION**

Xingyu Zhou, Beijing Institute of Technology; Qiao Dong, Beijing Institute of Technology; Changxuan Wen, Beijing Institute of Technology; Hongwei Han, Beijing Institute of Technology

This paper proposes a distributed sequential convex optimization (DSCO) method for large-scale fuel-optimal swarm migration problems. The optimal control problem (OCP) under collision avoidance constraints is formulated. The coupled collision avoidance constrains are decoupled in an iterative framework based on the nominal trajectory. An iterative update strategy and a convergence judgment strategy are proposed to improve the robustness and efficiency of the algorithm. Then sequential convex programming (SCP) is used to solve the distributed sub-problems. Finally, the proposed DSCO is successfully applid to a 100-spacecrafts swarm migration problem.

10:54 **AAS 21-341** **Nonlinear Mapping of Orbit Element Differences for Spacecraft Formation Flying**

Ayansola Ogundele, National Space Research and Development Agency; Olufemi Agboola, National Space Research and Development Agency, Nigeria

The increase in interest in spacecraft formation flying concept necessitated the need to design and develop a high fidelity dynamical models for future space missions. In this paper, to improve the dynamics fidelity, higher order relative motion model is developed using orbit element differences. The nonlinear mapping between orbit element differences and Hill coordinates are established using Taylor series expansion. Using the nonlinear mapped relationship, radial, along-track and cross-track positions and velocities are developed. Afterward, new state transition matrix and bounded relative motion are developed for both circular and elliptical chief orbits. A comparison is made with the existing models.

11:06 **AAS 21-348** **Satellite Formation Reconfiguration and the Traveling Salesman Problem**

Kyle T. Alfriend, Texas A&M University

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

11:18 **AAS 21-373** **Closed Form Solution of Nonlinear J2 Perturbed Spacecraft Formation Flying in Elliptical Orbit**

Ayansola Ogundele, National Space Research and Development Agency; Olufemi Agboola, National Space Research and Development Agency, Nigeria

In this paper, closed form solution of nonlinear J2 perturbed spacecraft formation flying in elliptical orbit is developed via power series approach. The power series method is one of the most widely used and powerful analytic methods for constructing solutions of linear and nonlinear differential equations. Quadratic approximation form of the J2 perturbed relative motion was formulated by retaining quadratic nonlinear terms. Afterward, power series solution technique was applied to develop analytical solutions of the motion. The new model is compared numerically with the nonlinear J2 perturbed motion.

11:30 **AAS 21-451** **Spacecraft Formation Control Near a Periodic Orbit Using Geometric Relative Coordinates**

Ian Elliott, University of Colorado Boulder; Natasha Bosanac, University of Colorado, Boulder

A nonlinear feedback control law is introduced to establish relative motion about a periodic orbit with oscillatory modes in the circular restricted three-body problem. The control law feeds back errors in terms of geometric relative coordinates defined using nearby quasi-periodic motion. This definition of the tracking error enables straightforward feedbackgain selection via geometric insight. The control law is used to stabilize a spacecraft to follow first-order quasi-periodic motion relative to a periodic orbit, requiring low control effort to maintain long-term bounded relative motion in the circular restricted three-body problem.

11:42 **AAS 21-448** **Spacecraft Swarms for Monitoring Active Earth Features**

Jekan Thangavelautham, University of Arizona

In this work, we develop swarm mission conceptsfor monitoring active Earth features with Synthetic Aperture Radar (SAR). To achieve this, we develop probabilistic coverage algorithms for different operational modes of SAR. These algorithms are used to design the seed spacecraft orbits, which are then used to design a constellation that maximizes the spatio-temporal coverage. We then examine the reconfiguration problem, where once an active feature is detected, the spacecraft perform maneuvers to maximize the temporal coverage of the feature. Finally, we demonstrate the algorithms through numerical simulations to design a SAR-based swarm to detect and monitor volcanoes.

Feb 3, 2021 Virtual Room #3

23 - Guidance, Navigation, and Control

Chair: Marcus Holzinger, University of Colorado Boulder

10:30 **AAS 21-260** **Optimal reference orbit tracking around asteroids via Particle Swarm Optimization and inverse dynamics technique**

Andrea D'Ambrosio, Sapienza Università di Roma; Andrea Carbone, School of Aerospace Engineering, Sapienza University of Rome; Marco Mastrofini, School of Aerospace

Engineering, Sapienza University of Rome; Fabio Curti, School of Aerospace Engineering, Sapienza University of Rome

Optimal proximity operations around asteroids are very challenging because of their irregular gravity field. This paper focuses on optimal control applied to asteroids proximity maneuvers obtained thanks to the combination of Particle Swarm Optimization, inverse dynamics and B-splines, used to approximate the trajectory. Furthermore, an Extreme Learning Machine-based algorithm is employed to estimate the gravity vector from the position vector in the asteroid body-fixed frame. This choice allows to achieve a good accuracy while decreasing the computational time that other precise methods, like the polyhedron model, would require. Finally, the proposed framework is applied to reference orbit tracking around asteroids.

10:42 **AAS 21-347** **Direct Visual SLAM with a Filter-Based Lidar Measurement Incorporation**

Corey Marcus, The University of Texas at Austin; Renato Zanetti, The University of Texas at Austin

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

10:54 **AAS 21-353** **Covariance Estimation using geometric optimization on symmetric positive definite manifolds**

Rahul Moghe, The University of Texas at Austin; Maruthi R. Akella, The University of Texas at Austin; Renato Zanetti, The University of Texas at Austin

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

11:06 **AAS 21-366** **Orbit Maintenance Strategy for Earth-Moon Halo Orbits**

Vivek Muralidharan, Purdue University; Kathleen C. Howell, Purdue University

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

11:18 AAS 21-397 INVESTIGATION OF KEY GYRO PERFORMANCE CRITERIA: OPTIMIZATION VIA META-ANALYSIS CORRELATIONS

Martin Hasha, Lockheed Martin Space Company

Inertial Reference Units (IRUs) are crucialto achieving spacecraft Line-of-Sight (LOS) fine-pointing performance. Allocated criteria (e.g. drift, bias, etc.) present profound challenges for assessing unit limits and trade-off weighting lacking statistically-significant data. A unique data-mining meta-analysis is performed on large datasets of in-family, flight-accepted Hemispherical Resonating Gyros (HRGs), addressing multiple parameters. Evaluation via bivariate correlations (Pearson's coefficients) is intended to extract previously unexplored/unknown insights. Cost reductions, while meeting overall limits, is discussed. Data aggregations, conclusions, and methods are valuable in LOS jitter models, analyses, and optimizing wide-ranging space applications: e.g. steering mirrors, cryocoolers, moving antenna, microgravity platforms, planetary flybys, etc.

11:30 AAS 21-416 Estimation Of The Conditional State And Covariance with Taylor Polynomials

Simone Servadio, The Universityof Texas at Austin; Renato Zanetti, The Universityof Texas at Austin

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

11:42 AAS 21-439 Orion GN&C Sequencing for Off-Nominal Rendezvous, Proximity Operations, and Docking

Jordan Abell, University of Colorado Boulder; Peter Schulte, The Charles Stark Draper Laboratory, Inc.; Fred Clark, Draper; Peter Spehar, NASA Johnson Space Center; David Woffinden, NASA Johnson Space Center

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

Feb 3, 2021Virtual Room #4

24 - Orbit Determination

Chair: Kyle DeMars, Texas A&M University

10:30 AAS 21-280 Comparison and Error Modeling of Velocity Initial Orbit Determination Algorithms

Linyi Hou, University of Illinois at Urbana-Champaign; Kevin Lohan, University of Illinois at Urbana-Champaign; Zachary Putnam, University of Illinois at Urbana-Champaign

Recently, Christian and Hollenberg proposed and solved a new class of initial orbit determination problems whereby a spacecraft's orbit is determined using only velocity measurements. This paper introduces a modification to the velocity initial orbit determination algorithm that improves both accuracy and computationalefficiency. Changes in the orbit determination error with respect to semi-major axis, eccentricity, true anomaly, sensor noise, measurement duration, and number of measurements are then analytically modeled using the orbit hodograph. Finally, the analytic model is compared against Monte Carlo simulations using the improved algorithm. Results show the analytic model accurately predicts changes inorbit determination error.

10:42 AAS 21-309 Towards Accurate Orbit Determination using Semi-analytical Satellite Theory
Bryan Cazabonne, CS GROUP; Paul J. Cefola, University at Buffalo (SUNY)

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

10:54 AAS 21-314 Nonlinear Set-Membership Filtering-Based Orbit Estimation
Diganta Bhattacharjee, The University of Texas at Arlington; Kamesh Subbarao, University of Texas at Arlington

We propose a nonlinear set-membership filtering-based orbit estimation technique for Earth-orbiting satellites. The recursive set-membership filter utilizes the state dependent coefficient parameterization to acquire a pseudo-linear description of the governing nonlinear system. At every recursion, the filter requires solutions to two convex optimization problems and these solutions can be efficiently obtained. We have included details of the filter design, the nonlinear motion model for the satellite in orbit, and the nonlinear measurement model in the extended abstract. In the final version, we would include simulation results corresponding to the set-membership filter and would provide comparisons with other state estimation techniques.

11:06 AAS 21-326 Optimally Convergent Minimum-Time Space Object Search and Recovery
Sam Fedeler, Universityof Colorado at Boulder; Marcus Holzinger, Universityof Colorado Boulder; William Whitacre, Charles Starck Draper Laboratory

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

11:30 **AAS 21-338** **Orbit Determination Via Physics Informed Neural Networks**
Andrea Scorsoglio, University of Arizona; Roberto Furfaro, The University of Arizona

In this paper, a set of orbit determination problems are solved via Physics-Informed Neural Networks. The classical least squares estimate is used a baseline for the loss function using a set of noisy measurements. The state of the spacecraft is estimated at each epoch using a deep neural network. A penalizing term based on the differential equations modelling the dynamics of the problem is then added to the loss as a regularizing term. This ensure that the learned relationship between input and output is compliant with the physics of the problem.

11:42 **AAS 21-362** **The Improvement of Satellite Constellation GNSS Orbit Determination through the Incorporation of Intersatellite Ranging Measurements**
Byron Davis, Georgia Institute of Technology; Brian Gunter, Georgia Institute of Technology

Satellite-based Global Navigation Satellite System (GNSS) Precision Orbit Determination (POD) uses relative measurements of distance to GNSS satellites with known positions and velocities to estimate the overall state of the non-GNSS satellite. This study seeks to determine whether an overall gain can be made to the performance of a high-fidelity orbit determination scheme through the addition of relative intersatellite measurements between non-GNSS satellites in a constellation. The authors develop a simulation and estimation environment in JPL's Monte software to assess the capabilities of nanosatellites to perform POD with GNSS only and quantify gains to POD with additional crosslink observations.

11:54 **AAS 21-248** **Process Noise Covariance Modeling for Absolute and Relative Orbit Determination**
Nathan Stacey, Stanford University; Simone D'Amico, Stanford University

This paper develops analytical process noise covariance models for both absolute and relative orbit determination in a discrete-time Kalman filtering framework. A model of the process noise covariance of a Cartesian spacecraft state is obtained for near-circular orbits by leveraging the solution of the Hill-Clohessy-Wiltshire equations parameterized in curvilinear coordinates. Absolute orbital element process noise covariance models are obtained by either assuming a near-circular orbit or a small propagation interval. Process noise covariance models for relative spacecraft states are then constructed from the developed absolute spacecraft state process noise covariance models. The presented models are validated through numerical simulations.

Feb 3, 2021Virtual Room #5

25 - Orbital Dynamics, perturbations and Stability

Chair: Diane Davis, a.i. solutions, Inc.

10:30 **AAS 21-233** **Including the closed-form J_2^2 effect in DSST**
Juan Félix San-Juan, University of La Rioja; Rosario López, University of La Rioja; Iván Pérez, University of La Rioja; Paul J. Cefola, University at Buffalo (SUNY)

A second-order closed-form semi-analytical solution of the main problem of the artificial satellite theory (J_2 problem) compatible with the Draper Semi-analytic Satellite Theory (DSST) is presented. The short-period terms are removed by means of an extension of the Lie-Deprit method using

Delaunay variables. The averaged equations of motion are given explicitly and transformed to the non-singular equinoctial elements. Finally, the second-order terms in the mean element equations of motion are included in the C/C++ version of the DSST orbit propagator.

10:42 AAS 21-240 Koopman operator theory applied to the J2 perturbed motion around an oblate planet

David Arnas, Massachusetts Institute of Technology; Richard Linares, Massachusetts Institute of Technology

This manuscript analysis the solution provided by the Koopman operator methodology in its application to the main satellite problem. In this regard, this work performs an spectral study of the solution generated and compares it with the solution provided by the Poincar\'e-Lindstedt method. In addition, this manuscript introduces a perturbation methodology based on the Koopman operator to study perturbed systems. Several examples of application of these methodologies are included to show their performance under different conditions.

10:54 AAS 21-303 Modern Numerical Programming with Julia for Astrodynamic Trajectory Design

Dan Padilha, University of Tokyo / JAXA Institute of Space and Astronautical Science; Diogene Alessandro Dei Tos, JAXA; Nicola Baresi, University of Surrey; Junichiro Kawaguchi, JAXA

A programming toolkit is developed to leverage Julia, a high-performance numerical programming language, in the generation, optimisation, and analysis of orbital trajectories. Julia combines high-level abstraction with the computational efficiency of dynamic compilation, enabling highly composable and extensible programs and state-of-the-art performance in differential systems, statistical analysis, and machine learning. This paper outlines the motivations and consequences of Julia's multiple dispatch and meta-programming capabilities, and demonstrates new techniques enabled in the design of ballistic capture trajectories for a JAXA planetary exploration mission. The resulting toolkit's composability, extensibility, and performance is compared to JAXA's in-house jTOP trajectory propagation and optimisation tool.

11:06 AAS 21-335 The Terrestrial Exoplanet Simulator: An orbital propagator with optimal error growth following Brouwer's law

Peter Bartram, University of Southampton; Alexander Wittig, University of Southampton

We present the TES, a new error-optimal n-body integrator for propagating systems dominated by a central mass that permits close encounters and achieves a relative energy error at machine precision, i.e. 10^{-16}, for 10^5 orbits. TES refines the classicalEncke method with a series of numerical improvements that reduce both integration runtime and numerical error. The performance of TES is highly favourable for long-term evolution and close encounters of near Earth objects, such as Apophis, are propagated precisely. TES can be extended to support arbitrary perturbing forces, making it suitable for highly accurate long-term integration of satellites in the LEO environment.

11:18 AAS 21-352 Energy and Phasing Considerations for Low-Energy Transfers from Cislunar to Heliocentric Space

Kenza Boudad, Purdue University; Kathleen C. Howell, Purdue University; Diane Davis, a.i. solutions, Inc.

In the next decades, multiple missions are proposed or planned to originate in the vicinity of the Moon and be delivered to heliocentric space, such as departures from Gateway to interplanetary destinations. The Earth-Moon-Sun transit dynamics are complex, primarily influenced by the Earth and the Moon in cislunar space; the gravitational influence of the Sun becomes significant after departure from the Earth-Moon vicinity. The current investigation leverages an Earth-Moon-Sun-spacecraft four-body model, the Bicircular Restricted Four-Body Problem, including dynamical structures in this regime to explore natural motion between the lunar vicinity and orbits near the Sun-Earth libration points.

11:30 **AAS 21-365** **An Analysis of Koopman-based Perturbation Theory Applied to the Motion About an Oblate Planet**

David Arnas, Massachusetts Institute of Technology; Richard Linares, Massachusetts Institute of Technology; Kyle T. Alfriend, Texas A&M University

This paper investigates perturbation methods for satellite motion using the Koopman Operator (KO) in combination with Lie Series methods. The goal of this work is to compute near-identity Canonical Transformations (CT) that simplifies Hamiltonian systems and allows for the removal of fast periodic terms. The KO is used to numerically compute the CT that achieves the intend simplification. This work applies the proposed approach to the motion about an oblate planet were only the zonal terms are considered.

11:42 **AAS 21-375** **SRP-J2 Resonances in Low Earth Orbits for Objects with a Time-Variant Area-to-Mass Ratio**

Catherine Massé, McGill University; Inna Sharf, Mcgill University; Florent Deleflie, IMCCE / Paris Observatory

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

Feb 3, 2021Virtual Room #1

26 - Trajectory Design III

Chair: Rohan Sood, The University of Alabama

13:30 **AAS 21-229** **Aerocapture Trajectories for Earth Orbit Technology Demonstration and Orbiter Science Missions at Venus, Mars, and Neptune**

William Strauss, Jet Propulsion Laboratory; Alex Austin, Jet Propulsion Laboratory/California Institute of Technology

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

13:42 **AAS 21-243** **A Rapid Target-Search Technique for KBO Exploration Trajectories**

Miguel Benayas Penas, Catholic University of America ; Kyle Hughes, NASA Goddard Space Flight Center; Bruno Sarli, NASA/GSFC Science Collaborator; Donald Ellison, NASA Goddard Space Flight Center; Kevin Cowan, Delft University of Technology

A rapid, grid-based, target-search algorithm is presented to find candidate sequences of small-body encounters for mission design. The algorithm is especially relevant for cases with large combinatorial spaces. In this paper, the algorithm is used to identify candidate flyby sequences of multiple Kuiper-Belt Objects (KBOs). The target-search algorithm consists of four sequential steps: (1) parameter definition, (2) fine-tuned Lambert-based grid search of ballistic trajectories visiting one KBO, (3) rapid, delta V-based proximity search for additional KBOs using the state transition matrices, and (4) trajectory optimization of the most promising KBO sequences using the Evolutionary Mission Trajectory Generator (EMTG).

13:54 **AAS 21-289** **Combined b-plane and Picard-Chebyshev approach for the continuous design of perturbed interplanetary resonant trajectories**

Alessandro Masat, Politecnico di Milano; Matteo Romano, Politecnico di Milano; Camilla Colombo, Politecnico di Milano

Orbital resonances have been exploited in different contexts, with the latest interplanetary application being the ESA/NASA mission Solar Orbiter, which uses repeated flybys of Venus to change the ecliptic inclination with low fuel consumption. The b-plane formalism is a smart framework to design flybys at the boundaries of the sphere of influence with. The theory is applied in conjunction with the Picard-Chebyshev integration method as optimal pruning to the continuous design of perturbed resonant interplanetary trajectories in reverse cascade, based on models and analyses from previous works. This semi-analytical strategy may allow to surf generic perturbing effects before optimizing artificial control actions. Applications include designing both planetary and interplanetary quasi-ballistic trajectories.

14:06 **AAS 21-292** **EQUULEUS launch window analysis and mission design**

Diogene Alessandro Dei Tos, JAXA; Takuya Chikazawa, University of Tokyo; Yosuke Kawabata, The Universityof Tokyo; Kota Kakihara, The Universityof Tokyo; Nicola Baresi, University of Surrey; Stefano Campagnola, Jet Propulsion Laboratory; Yasuhiro Kawakatsu, JAXA / ISAS

This paper presents the trajectory design of EQUULEUS, a CubeSat scheduled to launch as a piggyback of Artemis 1. EQUULEUS will maneuver to a quasi-halo in 1-to-4 resonance with the Moon. As a secondary payload, the trajectory must be compatible with the requirements of the primary mission, but also robust against disturbances and changes in the deployment state. Realistic initial conditions are processed and the solution structure for optimal lunar transfers is analyzed. A host of candidate solutions is presented, compatibly with fuel and power limitations.
The understanding of the solution space is shown to be insightful for the design of robust trajectories for limited spacecraft.

14:18 **AAS 21-372** **Study on Interplanetary Trajectories towards Uranus and Neptune**

Francesco Sena, Department of Mechanical and Aerospace Engineering, Sapienza Universityof Rome; Andrea D'Ambrosio, Sapienza Università di Roma; Fabio Curti, School of Aerospace Engineering, Sapienza University of Rome

To better understand the origin and evolution of our Solar System, the Ice Giants could represent a coveted destination in future decades. In this work, possible trajectories towards Uranus and Neptune have been investigated. Using PyKEP and PyGMO, the Multiple Gravity-Assist (MGA) and the Multiple Gravity Assist with One Deep-Space-Maneuver per leg (MGA-1DSM) problems have been solved. In the simple MGA case, also a powered gravity-assist has been considered. Our analysis shows that feasible trajectories towards Uranus and Neptune can be obtained with a propellant usage in term of Δv the order of 2 km/s.

14:30 **AAS 21-377** **Preliminary Mission Design for Proposed NuSol Probe**

Kyle Messick, Wichita State University; Atri Dutta, Wichita State University; Holger Meyer; Mark Christl; Nick Solomey

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

14:42 **AAS 21-399** **Acceleration-Based Indirect Method for Continuous and Impulsive Trajectory Design**

Ehsan Taheri, Auburn University; Vishala Arya, Texas A & M University

A novel acceleration-based formulation is proposed to construct minimum-Δv bang-off-bang thrust profiles and impulsive maneuvers in a rapid manner. Substantial simplifications are achieved by removing mass as one of the states and thrust magnitude and specific impulse value as parameters from problem formulation. Standard acceleration-based optimization problems lead to trajectories whose solution lie entirely on a singular arc. To enforce bang-off-bang controlstructures, a maximum acceleration parameter is introduced to obtain impulsive solutions. Utility of the method is demonstrated for transfer maneuvers between orbits in two-body dynamics and in the circular restricted three-body problem.

14:54 **AAS 21-426** **Interplanetary Trajectory Design for a Hybrid Photonic-Electric Propulsion System Departing from Cislunar Orbits**

Yuki Takao, Japan Aerospace Exploration Agency; Toshihiro Chujo, Tokyo Institute of Technology

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

27 - Guidance and Control

Chair: Atri Dutta, Wichita State University

13:30 **AAS 21-208** **Autonomous Spacecraft Obstacle Avoidance and Trajectory Tracking in a Dense Debris Field**

Madhur Tiwari, Embry-Riddle Aeronautical University; David Zuehlke, Embry-Riddle Aeronautical University; Richard Prazenica, Embry-Riddle Aeronautical University ; Troy Henderson, Embry-Riddle Aeronautical University

An autonomous path planning technique using artificial potential functions paired with a direct adaptive controller is implemented for spacecraft trajectory tracking through a dense debris field. The debris field is modeled using relative orbital dynamics with disturbances and the spacecraft is modeled using two-body nonlinear dynamics and perturbations. The spacecraft is assumed to be in proximity to a dense debris field that it must navigate through to reach a goal destination. A direct adaptive controller is implemented to track generated trajectories using artificial potential functions to achieve robust tracking in the presence of model and path uncertainties.

13:42 **AAS 21-258** **Class of Optimal Space Guidance Problems solved via Indirect Methods and Physics-Informed Neural Networks**

Enrico Schiassi, University of Arizona; Andrea D'Ambrosio, Sapienza Università di Roma; Andrea Scorsoglio, University of Arizona; Roberto Furfaro, The University of Arizona; Fabio Curti, School of Aerospace Engineering, Sapienza University of Rome

In this work, optimal space guidance control problems are faced using indirect methods and Physics-Informed Neural Networks (PINNs), whose training is driven by the dynamics equations. The boundary value problem arising from the Pontryagin Minimum Principle is solved both via standard PINNs and the Extreme Theory of Functional Connections (X-TFC). With X-TFC, the boundary conditions are analytically satisfied thanks to the so-called Constrained Expressions, introduced with the original Theory of Functional Connections (TFC). These expressions are a sum of a free-function, expanded as a neural network trained via Extreme Learning Machine, and a functional that analytically satisfies the boundary constraints.

13:54 **AAS 21-259** **Physics-Informed Neural Networks Appliedto a Series of Constrained Space Guidance Problems**

Andrea D'Ambrosio, Sapienza Università di Roma; Enrico Schiassi, University of Arizona; Roberto Furfaro, The Universityof Arizona; Fabio Curti, School of Aerospace Engineering, Sapienza University of Rome

Extreme Theory of Functional Connections (X-TFC) is exploited to solve constrained optimal control problems (COCP) via indirect method. The latent solutions are approximated using the so-called Constrained Expressions, which are the sum of a free-chosen function, represented by a single layer neural network trained via Extreme Learning Machine, and a functional that analytically satisfies the boundary conditions. Moreover, inequality constraints are considered and the COCP is transformed into an unconstrained optimal controlproblem introducing new variables and employing saturation functions. X-TFC is then used to solve the related boundary value problem. Results show great accuracy and low computational time.

14:06 **AAS 21-386** **REACTION WHEEL VIBRATIONAL JITTER META-ANALYSIS: INTEGRATIVE INSIGHTS VIA STATISTICAL CORRELATIONS**

Martin Hasha, Lockheed Martin Space Company

Reaction Wheel Assemblies (RWAs) are crucial to achieve stringent spacecraft Line-of-Sight (LOS) fine-pointing limits. Induced Vibrations (IVs) are judiciously allocated to contain deleterious jitter: handicapped when lacking sufficient statistically-significant data. An IV meta-analysis is undertaken via same-family dataset mining. Directionality, harmonics, and source diagnostics utilize bivariate correlations (Pearson's coefficients). Multiple key parameters are enlisted to discover previously unknown/unresolved relationships. Proven optimization methodologies, data results, issues, and conclusions are presented. Prior findings are expanded to extend to current/future RWAs. Data aggregations and insights are valuable for wide-ranging spacecraft applications: e.g. steering mirrors, cryocoolers, moving antenna, microgravity platforms, planetary flybys, etc.

14:18 **AAS 21-402** **Precision Attitude Stabilization with Intermittent External Torque**

Arjun Ram Subramani Purushothaman, The University of Texas at Austin; Maruthi R. Akella, The University of Texas at Austin

The attitude stabilization of a microsatellite employing a variable-amplitude cold-gas thruster which reflects as a time varying gain on the controlinput is considered. Existing literature uses a persistence filter based approach that typically leads to large control gains and torque inputs during specific time intervals corresponding to the "off" phase of the external actuation. This work aims at reducing the transient spikes placed upon the torque commands by the judicious introduction of an additional time varying scaling factor as part of the control law.

14:42 **AAS 21-441** **Perceptron Based Orbital Guidance in a Low Gravity Asteroid Environment**

Leonard Vance, University of Arizona

Feb 3, 2021 Virtual Room #3

28 - Dynamical System Theory II

Chair: Amanda Haapala , Johns Hopkins University Applied Physics Laboratory

13:30 **AAS 21-212** **Global L2 Quasi-Halo Family and their Characteristics**

David Lujan, University of Colorado Boulder; Daniel Scheeres, University of Colorado Boulder

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

13:42 **AAS 21-222** **A Rapid Method For Orbital Coverage Statistics With J2 Using Ergodic Theory**

Andrew Graven, Cornell University; Alan Barr, Department of Computing and Mathematical Sciences, California Institute of Technology; Martin Wen-Yu Lo, Jet Propulsion Laboratory

Quantifying long-term statistical properties of satellite trajectories typically entails time-consuming trajectory propagation. We present a fast, ergodic method of analytically estimating these for J2-perturbed elliptical orbits, broadly agreeing with trajectory propagation-derived results. We extend the approach in Graven and Lo (2019) to estimate: (1) Satellite-ground station coverage with limited satellite field of view and ground station elevation angle with numerically optimized formulae, and (2) long-term averages of general functions of satellite position. This method is fast enough to facilitate real-time, interactive tools for satellite constellation and network design, with an approximate 1000x GPU speedup.

13:54 **AAS 21-244** **Low-Energy Transfers between Planar and Spatial Periodic Orbits via Vertical Instability around Earth-Moon L1**

Kenta Oshima, Hiroshima Institute of Technology

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

14:18 **AAS 21-256** **Quasi-periodic Orbit Transfers Via Intersecting Torus Whiskers**

Damennick Henry, University of Colorado at Boulder; Daniel Scheeres, University of Colorado Boulder

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

14:30 **AAS 21-265** **CubeSat Lunar Transfer Design via Weak Stability Boundaries**

Danny Owen, University College London; Xiaoyu Fu, University of Surrey; Nicola Baresi, University of Surrey

CubeSat ride-share opportunities to lunar transfer orbit are becoming increasingly common. Low propellant budgets mean many of these CubeSats would benefit from low-energy trajectories. Design of such trajectories can be computationally intensive. We propose an investigation into patterns of orbital parameters mapped to the Moon B-plane that allow for low-energy lunar trajectory design for CubeSats that are initially placed into a free-return trajectory as secondary payloads. This will result in tools to make such trajectory design quicker and easier. This is achieved via a grid search method in which forward and backward propagated trajectories are paired at a mutual patching point.

Feb 3, 2021Virtual Room #4

29 - Space Robotics and Autonomous Operation

Chair: Jay McMahon, University of Colorado Boulder

13:30 **AAS 21-213** **A Unique Robotic Manipulator for Application in Hardware-In-The-Loop Simulations of On-Orbit Servicing Missions**

Anirudh Chhabra, University of Cincinnati; Donghoon Kim, University of Cincinnati

Autonomous on-orbit servicing missions require high precision because any unwanted contact forces can cause damage to space systems. This makes the on-ground hardware-in-the-loop simulations necessary as operations must be thoroughly evaluated before such missions are carried out in space. A unique robotic structure is proposed where a robotic arm is linked with a Stewart platform. Mathematical models are developed for systems with different robotic arms having varying degrees of freedom and the corresponding dynamics are formulated. Simulation studies are conducted for capturing scaled-down orbitaltrajectories by using an optimal controlscheme and identify the system with desired range and accuracy.

13:42 **AAS 21-224** **Study of Spacecraft Deployables Failures**

Alejandro Rivera, NASA Goddard Space Flight Center

Unsuccessful deployments of solar arrays, antennas and other spacecraft deployable appendages are one of the main causes of initial satellite failures and reduction in their capabilities with approximately one failure every two years, which result in extremely large insurance claims. This paper examines publically known spacecraft deployables failures and anomalies that have occurred since 1968 on a total of 40 different spacecraft, and that can be directly attributed to deployment issues. Information is used to build a case for a robotic servicing mission. Concepts for three possible robotic tools and the novel technologies they employ are then briefly described.

13:54 **AAS 21-238** **Genetic Fuzzy System-Based Multi-Robot Coordination for Planetary Missions**

Daegyun Choi, University of Cincinnati; Donghoon Kim, University of Cincinnati

In the planet exploration missions, experimental devices without mobility may require relocating to perform further missions. To transport objects like experimental devices, a multi-robot system (MRS) has become popular in recent decades due to its benefits. In this research, an object transportation problem with an MRS is dealt with by using a fuzzy inference system in the manner of decentralized control. The parameters of membership functions and the rule-base are trained by a genetic algorithm with various training scenarios to find the best fit solution, and the trained fuzzy inference system is validated by using several testing scenarios.

14:06 **AAS 21-382** **COLLISION AVOIDANCE AND FORMATION FLYING FOR NASA ASTROBEE ROBOTS USING PREDICTIVE CONTROL AND MACHINE LEARNI NG**

Isuru Basnayake, New Maxico State University; Hyeongjun Park, New Mexico State University

Using multiple NASA Astrobee robots in a confined space such as the International Space Station (ISS) increases the chance of a collision. This requires employing a formation control and collision avoidance framework for the three Astrobees operating in the ISS. Model predictive control (MPC) would be the best candidate for this task. However, machine learning techniques can be utilized to reduce the online computation burden of MPC. In this paper, we develop a control framework based on nonlinear MPC with improved for efficient online control by employing machine learning techniques, for the formation control and collision avoidance of the Astrobees inISS.

14:18 AAS 21-421 Safe and Uncertainty-Aware Robotic Motion Planning Techniques for Agile On-Orbit Assembly

Bryce Doerr, Massachusetts Institute of Technology; Keenan Albee, Massachusetts Institute of Technology; Monica Ekal, Instituto Superior Técnico; Richard Linares, Massachusetts Institute of Technology; Rodrigo Ventura, Instituto Superior Técnico, University of Lisbon

As access to space and robotic autonomy capabilities move forward, there is simultaneously a growing interest in deploying large, complex space structures to provide new on-orbit capabilities. New space-borne observatories, large orbital outposts, and even futuristic on-orbit manufacturing will be enabled by robotic assembly of space structures using techniques like on-orbit additive manufacturing which can provide flexibility in constructing and even repairing complex hardware. The contribution of this work is to address both the motion planning and controlfor robotic assembly with consideration of the inertial estimation of the combined robotic assembler and additively manufactured component system.

14:30 AAS 21-446 Catalyst: A Platform for Autonomous Tactical Multi-Spacecraft Aggregation

Jekan Thangavelautham, University of Arizona

14:42 AAS 21-449 MAXIMIZING DUST DEVIL FOLLOW-UP OBSERVATIONS ON MARS USING CUBESATS AND ON-BOARD SCHEDULI NG

Robyn Woollands, University of Illinois at Urbana-Champaign; Federico Rossi, Jet Propulsion Laboratory, California Institute of Technology; Tiago Stegun Vaquero, Jet Propulsion Laboratory, California Institute of Technology; Marc Sanchez Net, Jet Propulsion Laboratory, California Institute of Technology; Suyun Bae, Jet Propulsion Laboratory, California Institute of Technology; Joshua Vander Hook, Jet Propulsion Laboratory, California Institute of Technology

Several million dust devil events occur on Mars every day. These events last about 30 minutes and range in size from meters to hundreds of meters in diameter. Designing low-cost missions that will improve our knowledge of dust devil formation and evolution is fundamental to informing future crewed Mars lander missions about surface conditions. In this paper we present a mission design methodology for a constellation of low orbiting Mars cubesats, each carrying imagers with agile pointing capabilities. The goal is to maximize the number of dust devil follow-up observations through real-time, on-board scheduling.

14:54 **AAS 21-447** **FemtoSats for Exploring Permanently Shadowed Regions on the Moon**
Jekan Thangavelautham, University of Arizona

Feb 3, 2021Virtual Room #5

30 - Multi Object Tracking

Chair: Richard Linares, Massachusetts Institute of Technology

13:30 **AAS 21-236** **Space Object Tracking at the Purdue Optical Ground Station**
Patrick Kelly, Texas A&M University; Carolin Frueh, Purdue University

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

13:42 **AAS 21-339** **Joint Probabilistic Data Association Filter Using Alternate Equinoctial Orbital Elements**
John Helmuth, Texas A&M University; Kyle DeMars, Texas A&M University

Space surveillance is a challenging problem, which grows more difficult with each new object in orbit. Loss of satellite custody can lead to dangerous consequences such as collisions resulting in destruction of expensive resources and a dramatic increase in debris. This paper merges the joint probabilistic data association filter with alternate equinoctial orbital elements to create an improved framework for space object tracking and comparesthe approach to a JPDAfilter with Cartesian states in numerical experiments.

14:06 **AAS 21-228** **Autonomous Spacecraft Tasking using Monte Carlo Tree Search Methods**
Adam Herrmann, University of Colorado, Boulder; Hanspeter Schaub, University of Colorado

This work explores the use of Monte Carlo tree search (MCTS) methods as a form of value iteration to solve the Earth-observing satellite scheduling problem, expanding on prior work by comparing neural network regression over MCTS state-action pairs to a variation of AlphaZero, which continually improves upon the value network by executing it as the rollout policy in MCTS. An in-depth hyperparameter search is conducted for both algorithms, which are compared on the basis of performance, safety, and downlink opportunity utilization. Furthermore, each trained network is executed in a stochastic version of the Earth-observing satellite environment to measure robustness to uncertainty.

14:18 AAS 21-364 Autonomous Satellite Detection and Tracking using Optical Flow

David Zuehlke, Embry-Riddle Aeronautical University; Daniel Posada, Embry-Riddle Aeronautical University; Madhur Tiwari, Embry-Riddle Aeronautical University; Troy Henderson, Embry-Riddle Aeronautical University

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

14:30 AAS 21-427 APPLICATIONS OF A MCMC SAMPLING AND CLUSTERING METHODS BASED RANDOMIZED-FINITE SET STATISTICS TECHNIQUE (R-FISST II)

Utkarsh Mishra, Texas A&M University; Suman Chakravorty, Texas A&M University; Weston Faber, Applied Defense Solutions; Islam Hussein, Thornton Tomasetti

This paper presents a novel approach to keeping the Random Finite Set (RFS)based Bayesian recursions tractable. We propose a randomized scheme using aMetropolis-Hastings, Markov Chain Monte Carlo (MCMC), based technique and Finite Set Statistics (FISST), termed Randomized FISST II (R-FISST II). This technique samples highly probable target-observation association hypotheses and uses them to approximate the posterior RFS based multi-object Probability Den-sity Function (PDF). Finally, we demonstrate the performances of this tracker for a multiple space object tracking problem with heavy clutter. We compare and contrast this method with a Multi target tracking method based on Murthy's K-best assignment algorithm.

14:42 AAS 21-271 Orbit Determination Using the Probability Hypothesis Density Filter and Alternate Equinoctial Orbital Elements

James Brouk, Texas A&M University; Kyle DeMars, Texas A&M University

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

Authors

Dutta, Soumyo 09 - Atmospheric Reentry Guidance and Control

Chairs

Abdelkhalik, Ossama 17 - Spacecraft Control II (Author)
Blazquez, Emmanuel 11 - Low Thrust Trajectories II
Bosanac, Natasha 06 - Low Thrust Trajectories I (Author)
Boudad, Kenza 25 - Orbital Dynamics, perturbations and Stability (Author)
Boutonnet, Arnaud 11 - Low Thrust Trajectories II (Author)
Choi, Daegyun 15 Dynamical System Theory I (Author)
Curti, Fabio 03 - Rendezvous (Author) , 13 - Spacecraft Control I (Author)
Davis, Diane 25 - Orbital Dynamics, perturbations and Stability (Author)
DeMars, Kyle 24 - Orbit Determination (Author)
Dutta, Atri 27 - Guidance and Control (Author)
Furfaro, Roberto 05 - Asteroids I (Author) , 17 - Spacecraft Control II (Author)
Ghosh, Pradipto 09 - Atmospheric Reentry Guidance and Control (Author)
Gunter, Brian 08 - Navigation (Author)
Haapala , Amanda 28 - Dynamical System Theory II (Author)
Hernandez, Sonia 21 - Trajectory Optimization (Author)
Holzinger, Marcus 23 - Guidance, Navigation, and Control (Author)
Howell, Kathleen C. 01 - Interplanetary Trajectories (Author)
Jones, Brandon 14 - Cislunar Space Situational Awareness (Author)
Kim, Donghoon 15 Dynamical System Theory I (Author)
Lai, Peter 10 - Artificial Intelligence in Astrodynamics (Author)
Linares, Richard 30 - Multi Object Tracking (Author)
Majji, Manoranjan 20 - Space Robotics and Autonomous Operation & Lunar (Author)
Mashiku, Alinda 02 - Debris Clouds, Debris Densities, and Space Environment (Author) , 18 - Space Object Characterization and Independent Attitude Determination (Author)
McMahon, Jay 29 - Space Robotics and Autonomous Operation (Author)
Mehta, Piyush 02 - Debris Clouds, Debris Densities, and Space Environment (Author) , 18 - Space Object Characterization and Independent Attitude Determination (Author)
Melton, Robert 22 - Formation Flying (Author)
Rao, Anil 19 - Asteroids II & Mars (Author)
Roscoe, Christopher 04 - Satellite Formations & Collision Avoidance (Author)
Rubinsztejn, Ari 26 - Trajectory Design III (Author)
Sinclair, Andrew J. 07 - Attitude Dynamics and Control (Author)
Sood, Rohan 01 - Interplanetary Trajectories (Author) , 26 - Trajectory Design III (Author)
Thorne, James 12 - Trajectory Design I (Author)
Topputo, Francesco 03 - Rendezvous (Author) , 13 - Spacecraft Control I (Author)
Valerino, Powtawche 16 - Trajectory Design II (Author)