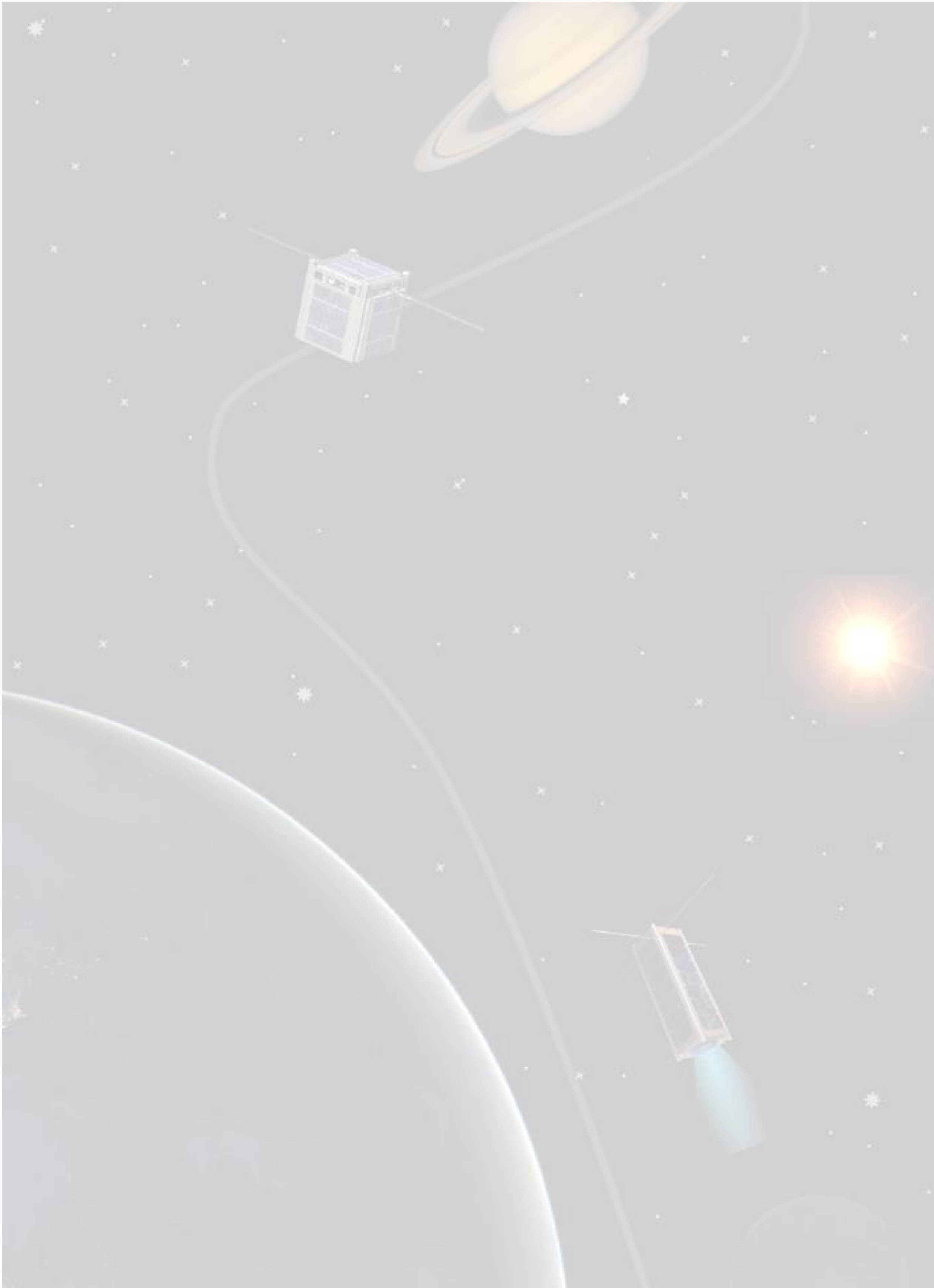
May 1-2, 2023

California Institute of Technology



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Conference Agenda

Monday, 1st May, 2023

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7:30-8:30	Registration and Breakfast
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9:45-10:00	Coffee break **(Sponsored by Glenair)**
10:00-12:00	**Session A: Lessons learned from interplanetary small satellite missions recently launched** *Session Chairs: A. Babuscia and M. Saing*
	A.1 BioSentinel Deep Space CubeSat Mission *(M. Napoli)* A.2 LunaH-Map: Early Operations, Science Data and Technology Demonstrations *(C. Hardgrove)* A.3 CAPSTONE: A Summary of a Highly Successful Mission in the Cislunar Environment *(T. Gardner)* A.4Taking pictures in Deep Space: ArgoMoon and LICIACube *(E. Fazzoletto)* A.5 Navigation of LICIACube: Challenges and Lessons learned *(L. Gomez)* A.6 A DSN Retrospective on CubeSat Support for Lunar Flashlight *(K. Buckmaster)* A.7 Highly accurate surface propagation for Mars Helicopter mission. *(N. Chahat)* A.8 Downsizing Mission Design for CubeSats *(D. Grebow)*
12:00-12:20	**Session A Q&A Panel: A. Babuscia and M. Saing**
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15:10-15:30	**Session B Q&A Panel: C. Lau and R. Nugent**
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15:45-17:45	**Session C: Ground support for interplanetary small satellite missions** *Session Chairs: K. Buckmaster and C. Lee*
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18:15-20:00	Dinner

Tuesday, May 2nd, 2023

Time (PDT)	Event
7:30-8:30	Registration and Breakfast
8:30-8:45	**Opening Remarks (A. Babuscia)**
8:45-9:45	**Keynote Speaker: Roger Walker (European Space Agency)** **Overview of ESA Lunar and Interplanetary CubeSat Missions** *Moderator: A. Babuscia*
9:45-10:00	Coffee break
10:00-12:00	**Session D: Incoming planned missions and innovative mission concepts** *Session Chairs: A. Babuscia and P. Clark*
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12:00-12:20	**Session D Q&A Panel: A. Babuscia and P. Clark**
12:20-13:10	Lunch
13:10-15:10	**Session E: Technologies for interplanetary small satellite missions** *Session Chairs: R. Nugent and J. Thangavelautham*
	E.1 Pelican: Radiation-tolerant Computational Storage *(J. Cerundolo)* E.2 Radioisotopic Propulsion for Small Satellites *(J. Pate)* E.3 FD04 Frangibolt Actuator Performance Test: Measuring Force and Stroke Margin *(I. Baho)* E.4 Ultrathin carbon nanotube freestanding thin films with specular reflective coatings for small satellites *(H. Tung)* E.5 Martian Lava Tube Exploration with Aerial Delivery Vehicle *(A. Dinkel)* E.6 Laser-based Localization of Robot Swarms for Lunar Infrastructure Construction Using Control Towers *(M. Kang)* E.7 Space Debris Remediation: Modeling of a Particle Cloud Momentum Interceptor *(J. Bartunek)* E.8 Lessons Learned Developing Lunar Flashlight Flight Software using the F Prime Product Line *(A. Rizvi)*
15:10-15:30	**Session E Q&A Panel: R. Nugent and J. Thangavelautham**
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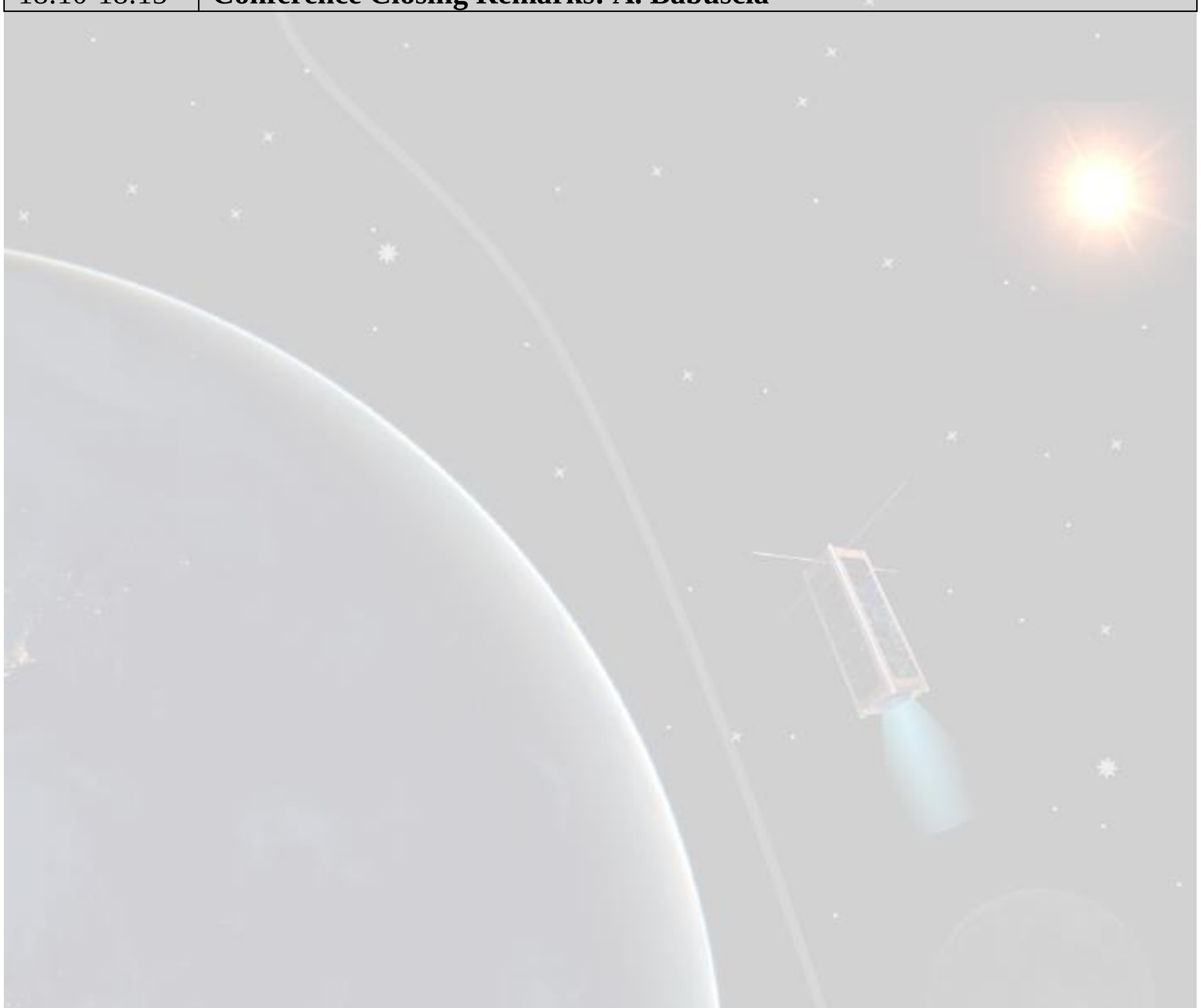
15:45-17:45	**Session F: Innovative interplanetary mission concepts and related technologies** *Session Chairs: M. Saing and C. Lau*
	F.1 Path planning and optimal trajectories for Mars sailplanes subject to stochastic atmospheric conditions *(A. Bouskela)* F.2 Fast transit outer planet exploration with small satellites *(A. Davoyan)* F.3 Flatworm-Inspired Robot for Extraterrestrial Exploration *(R. Cutler)* F.4 Energy Harvesting from Spacecraft Charging: An initial study using WarpX for PIC simulations *(A. Sam)* F.5 A Swarm Approach for Interstellar Object Intercept Missions *(V. Verma)* F.6 Evaluating the Feasibility of Emergency Response Using Network of Small Robots on a Lunar Base *(S. Muniyasamy)* F.7 CubeSat swarms in CisLunar space to identify, analyze, and characterize events of interest *(A. Raj)* F.8 Shape Memory Alloy Based Hard Docking Mechanisms for two-stage CubeSat Docking *(N. Gross)*
17:45-18:10	**Session F Q&A Panel: M. Saing and C. Lau**
18:10-18:15	**Conference Closing Remarks: A. Babuscia**



Welcome

Welcome to the 2023 Interplanetary Small Satellite Conference (ISSC), which will address the technical challenges, mission concepts, mission operations, and practicalities of space exploration with small satellites. This conference is organized by an evolving group of students, alumni, and staff from Caltech, NASA's Jet Propulsion Laboratory, the SpaceTreX Laboratory at University of Arizona, and DHV Technologies. The scope of ISSC is slightly broader than CubeSats only and it includes interplanetary small satellite missions or vehicles that do not fit into the CubeSat standard. This allows the conference to incorporate an important segment of the community, and to encourage the "outside the box" thinking that is critical to future interplanetary small satellite missions. Thank you for joining us in Caltech

— *The Organizing Committee*

Registration Hours and Contact Information

The registration desk will open from 7:30 am to 3pm on May 1. It will be open from 7:30 am to 3:00 pm on May 2. If you have any questions during the conference, please don't hesitate to contact the organizing committee at info@intersmallsatconference.org at any time during the conference.

Organizing Committee

Alessandra Babuscia received her B.S. and M.S degrees from the Politecnico di Milano, Milan, Italy, in 2005 and 2007, respectively, and her Ph.D. degree from the Massachusetts Institute of Technology (MIT), Cambridge, in 2012. She is a Telecommunication Product Delivery Manager at NASA JPL (337K). Currently, she is telecom lead for VERITAS mission, and she supports Clipper telecommunication engineering system team. In the small satellite domain, she leads the telecommunication efforts at TeamXc, and she is task manager at JPL for the following missions: LunaH-Map, LunarIce Cube and BioSentinel. Previously, she has been a telecommunication system engineer for Mars 2020, telecommunication lead for ASTERIA and RainCube missions at JPL, and PI for the Inflatable antenna for CubeSat effort. Before JPL, she has worked as a postdoctoral researcher and teaching assistant at MIT where she developed communication systems for different university missions (CASTOR, ExoplanetSat, Ter- Sat, REXIS, TALARIS).

Her current research interests include communication architecture design, statistical risk estimation, multidisciplinary design optimization, and mission scheduling and planning. She is a founding member for

ISSC since its first edition at MIT in 2012 (formerly known as iCubeSat), and she is a session chair at the IEEE Aerospace Conference.

Carlyn Lee is a software engineer for the Telecommunication Architecture Group at NASA Jet Propulsion Laboratory. She is involved in link budget analysis tools development and optimization for space communication and navigation. Her research interests include communication systems, networking architecture, and high performance computations.

Chi-Wung Lau is a member of the Signal Processing Research group at Jet Propulsion Laboratories. He has been working at JPL for 15 years and has been involved with such projects as Galileo, Deep Impact, MER, Phoenix, MSL, M2020 and VERITAS. Research areas of interest are 34 meter array tracking quantum communications, and link analysis. He received bachelor's from U.C. Berkeley in 1996 and master's from the University of Southern California in 2001.

Pamela Clark of the Advanced Instrument Concepts and Science Applications Group in the Instrument Division, at Jet Propulsion Laboratory, California Institute of Technology, is Technical Advisor of the JPL Cubesat Development Lab. She is also Science PI of the NASA EM1 Lunar IceCube Mission, as well as Convener and Program Chair for the Annual LunarCubes Workshops, and an adjunct research professor at Catholic University of America. She holds a PhD in Geochemical Remote Sensing from University of Maryland. Her interests include extending the cubesat paradigm to deep space technology demonstrations and science requirements driven cubesat missions, developing compact science instruments, evolving a low-cost development model for deep space missions, and using the cubesat paradigm to set up distributed networks for studying whole system dynamics. She is the author of several books, including

Remote Sensing Tools for Exploration, Constant-Scale Natural Boundary Mapping to Reveal Global and Cosmic Processes,and Dynamic Planet: Mercury in the Context of its Environment.

Ryan Nugent is currently the Country Manager for DHV Technology, a company that specializes in solar arrays and power subsystems for CubeSats and SmallSats. Prior to joining DHV Technology Ryan was a Co-Principal Investigator and Director of the Cal Poly CubeSat Lab at California Polytechnic State University, San Luis Obispo, which helped create and currently managed the CubeSat Design Specification (CDS). Ryan has spent 14 years with the program, starting as an undergraduate student and continuing as a graduate student in Aerospace Engineering. Ryan took a staff position at Cal Poly in 2011 and in 2021 took over as Director with the program. He has lead development efforts for Cal Poly dispenser designs, developing the processes required to support NASA, The U.S. Department of Defense, European Space Agency, and Commercial Organizations in certifying CubeSats, CubeSat components and CubeSat dispensers for domestic and international launches. Overall, Ryan has supported 23 orbital launches in the U.S. and internationally involving over 160 satellites, including the MarCO CubeSats.

Michael Saing is a Systems Engineer in the Project Systems Engineering and Formulation Section at the Jet Propulsion Laboratory (JPL). He is in the System Model, Analysis, and Architecture group and is a subject matter expert in space mission cost estimation and small satellites systems engineering. He is also one of the subsystem's engineer chair

for JPL's Foundry elite concurrent engineering design teams - TeamX, TeamXc, and ATeam.

Michael is also tasked by NASA Headquarters as a proposal reviewer, small satellites/ cubesats data collection, and model development. He graduated with an Aerospace Engineering degree (B.S.) from CSU Long Beach. After graduation, he started his early career work at the NASA Ames Research Center in Mountain View, CA prior to joining JPL. As an amateur backyard astronomer, his interests and hobbies are in the areas of astrophysics and heliophysics science, astrophotography, and telescopes.

Kris Angkasa is a Program Area Manager at Jet Propulsion Laboratory in the Interplanetary Network Directorate (IND), home of the NASA's Deep Space Network (DSN) and Multi-mission Ground Systems & Services (MGSS) programs.

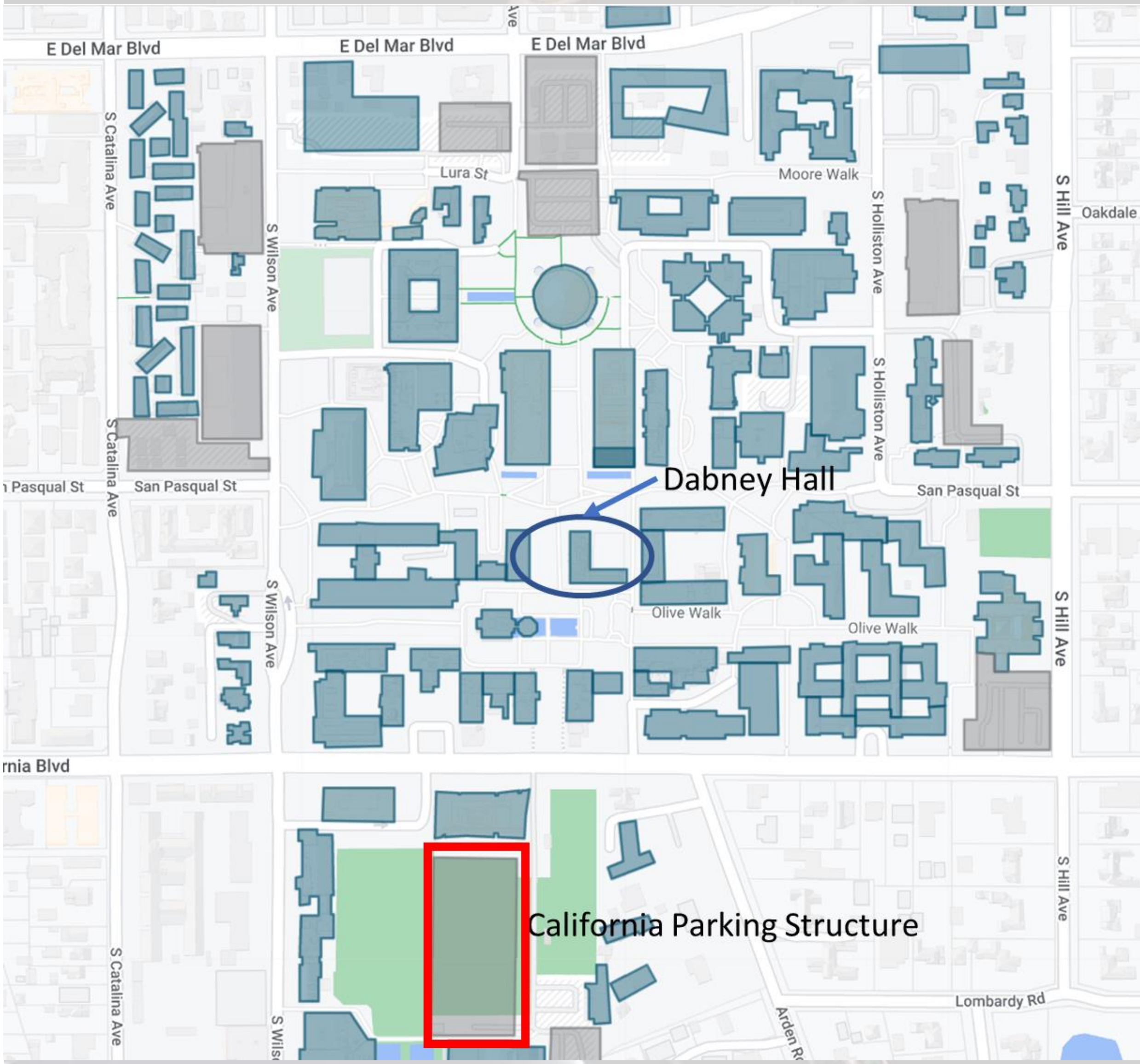
She has over 30 years of experience in space exploration, focusing her work in the DSN & space communication systems. Her efforts in the space industry include the development of a Ka-band TT&C subsystem for a commercial satellite at the Hughes Space & Communications. At JPL, her work includes the design, implementation, and testing of the DSN Block V Receiver and Flight Radios (SDST, Electra, Iris) for the flagship missions (Kepler, MER, MRO, MSL, Juno, MAVEN, and Mars 2020) as well as, the secondary payload CubeSats onboard Artemis I. Kris holds an MS degree in Electrical Engineering from the University of Southern California and a BS degree in Computer Science from the California Polytechnic University, Pomona.

Jekan Thanga has a background in aerospace engineering from the University of Toronto. He worked on Canadarm, Canadarm 2, and the DARPA Orbital Express missions at MDA Space Missions. Jekan obtained his Ph.D. in space robotics at the University of Toronto Institute for Aerospace Studies (UTIAS) and did his postdoctoral training at MIT's Field and Space Robotics Laboratory (FSRL). Jekan Thanga is an Associate Professor and heads the Space and Terrestrial Robotic Exploration (SpaceTREx) Laboratory and the NASA-funded ASTEROID (Asteroid Science, Technology and Exploration Research Organized by Inclusive eDucation) Center in Formation at the University of Arizona. He has been an advocate and leader in implementing Diversity, Equity and Inclusion programs in aerospace research, with nearly 300 graduate and undergraduate students matriculating through those programs. Jekan and his team of students have co-authored nearly 200 technical publications. He is the Engineering Principal Investigator on the AOSAT I CubeSat Centrifuge mission. He and his team of students were winners of the Popular Mechanics Breakthrough Award in 2016 for proposing the SunCube FemtoSat and won a Best Paper Presentation Award at AMOS 2019 for the Early Warning Constellation to Detect Incoming Meteor Threats. Jekan and his team of students were finalists for the NASA 2020 BIG Competition and winners of the 2021 NASA RASCAL Competition.

Kris Buckmaster is a Mission Interface Manager supporting NASA's Deep Space Network and Multimission Ground System and Services programs. After receiving a BS degree in Engineering Physics from Westmont College, he started his career in deep space tracking and communications in 2003, working on the operations and maintenance contract for the Deep Space Network doing critical events planning and operations engineering. Kris joined JPL in 2014 as a software systems engineer, focusing on ground data systems and provisioning CCSDS Space Link Extension services. He also worked as a systems engineer for NASA's Physical Oceanography Distributed Active Archive Center (PO.DAAC) for Tools and Services to make NASA's ocean and climate data accessible and meaningful. These days, he's sharpening his project management skills and enjoys applying agile software development practices to his work supporting a portfolio of missions that include both flagships like Europa Clipper, and cubesats like Lunar Flashlight.

Location, Venue, Parking, Covid-19 and Wifi Information

The conference will be at the Dabney Hall in Caltech, Pasadena. There are several parking structures around Caltech. The closest one is the California Parking structure highlighted in red in the map.



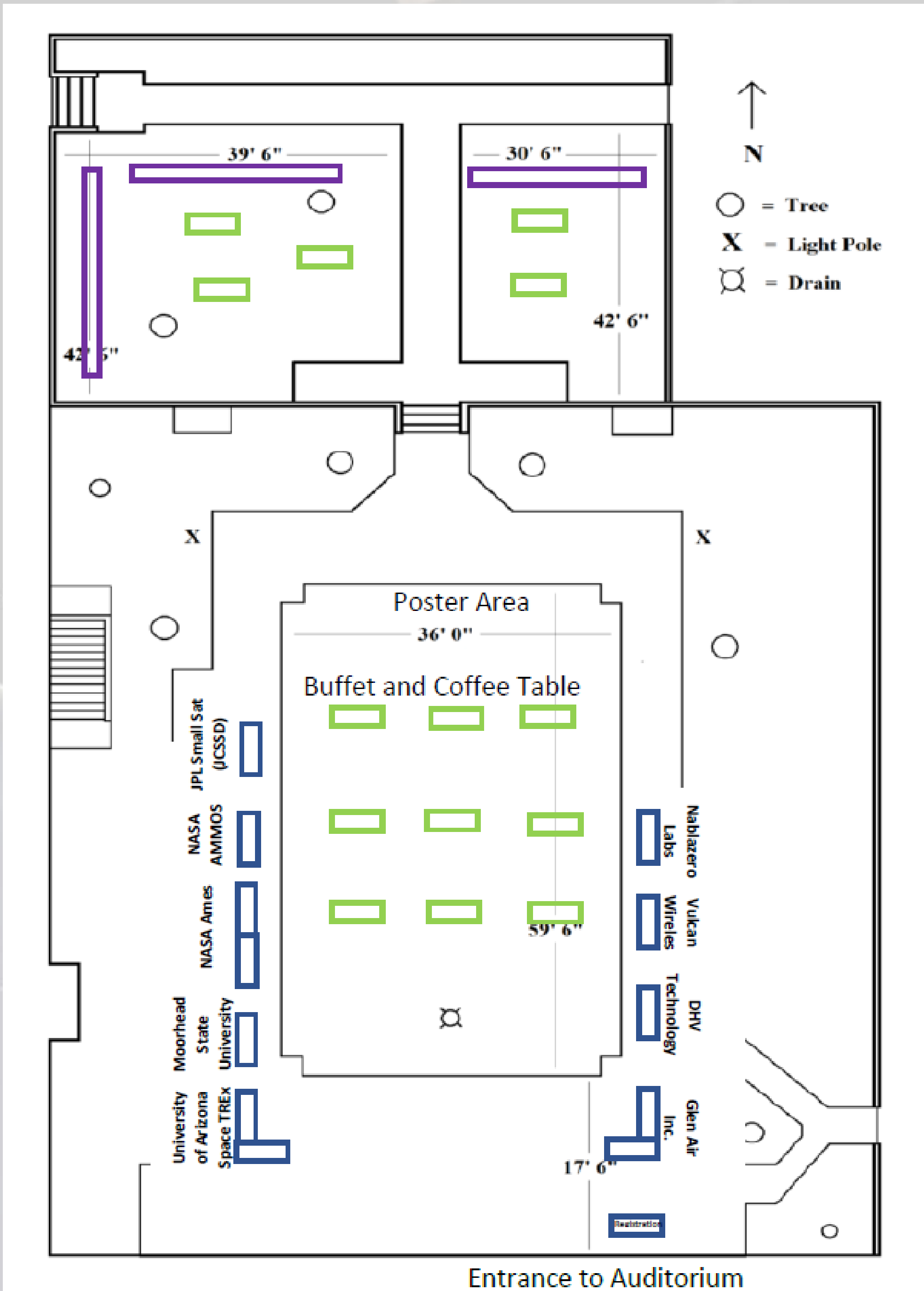
Parking permit can be payed directly at the pay stations. More information can be found: https://parking.caltech.edu/parking-info/visitor-parking

There are no COVID restrictions on Caltech campus at the time of printing this booklet. The conference organizers will post any changes to COVID-related policies to the ISSC website.

There will be a specific Wifi network setup at the conference. Password will be provided on site.

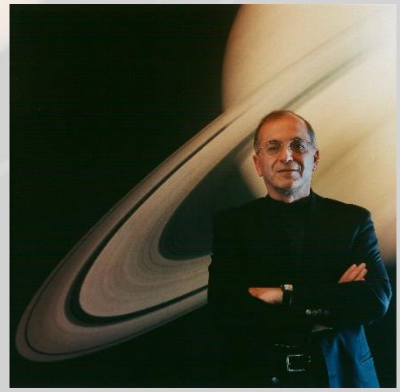
Registration Area, Conference Hall, Exhibitors and Meals Area Map

A rough map of the conference venue with exhibitors' tables and booths is shown below. Meals will be provided in the same exhibitors' courtyard.



Keynote Speaker Biographies

Dr. Charles Elachi



Experience and interest in the use of spaceborne active microwave instruments and remote sensing of planetary surfaces spheres and subsurfaces. Analysis and interpretation of radar imagery of planetary surfaces (including Earth).

During his 16-year tenure as JPL Director; JPL launched 24 mission: 2001-Genesis; 2001-Jason 1; 2001-Mars Odyssey; 2002-GRACE; 2003-GALEX; 2003-Opportunity; 2003-Spirit; 2003-Spitzer Space Telescope; 2005- Deep Impact; 2005-Mars Reconnaissance Orbiter; 2006-Cloudsat; 2007-Dawn; 2007-Phoenix; 2008-Jason 2; 2009-Kepler; 2009-NEOWISE; 2011-Aquarius; 2011-Curiosity; 2011-GRAIL; 2011-Juno; 2012-NuStar; 2014-OCO-2; 2015-SMAP; 2016-Jason 3.

Principal Investigator on a number of NASA research studies and development including: Analysis of the Apollo 17 radar imagery and profiles of lunar surface (1973-1976); Imaging Radar Oceanography (1975- 1977); Polar Ice Mapping and Dynamics (1977-1979); Shuttle Polar Ice Sheets Sounder (1978-1979); Comparative Imaging Radar Planetology (1977-1981); Earth Imaging Radar Geology (1977-1983); Electromagnetic sounding of a comet nucleus (1977-1980); Study of Venus clouds properties (1977-1980); Multispectral Titan Radar Imager/Sounder 1984-1987); Mars Altimetry (1984-1986). He has also participated in a number of mission development studies including Magellan, Seasat-A, LPO, Comet mission, Cassini and Mars Orbiter. He is responsible for a number of mission/sensors studies including: Shuttle Imaging Radar Series, Shuttle Scanning Altimeter, Shuttle Polar Ice Sheets Sounder and Titan Radar Mapper.

He is the author of 230 publications (including reports and conferences) and holder of four patents in the fields of space and planetary exploration, Earth observation from space, interpretation of active microwave remote sensing data, wave propagation and scattering, electromagnetic theory, lasers and integrated optics. He is the author-editor of the Chapter on "Microwave and Infrared Satellite Remote Sensors" which is in the new edition of the Manual of Remote Sensing (1983) and author of three textbooks on the "Physics and Techniques of Remote Sensing," "Spaceborne Radar Sensors," and "Radar Polarimetry".

Dr. Roger Walkers

Head of the ESA CubeSat Systems Unit, Projects Office, Systems Department, Directorate of Technology, Engineering & Quality.

Roger Walker has 15 years of experience at ESA in the CubeSat domain with 14 missions flown, from the beginnings of the CubeSat sector in Europe when they were mainly used as tools for hands-on education, to the present day working closely with a maturing European industry developing complex demonstrator and follow-on operational missions in Low Earth Orbit and beyond. For the last decade, he has been responsible for planning, preparing and implementing CubeSat missions for technology in-orbit demonstration with a growing team of system engineers. His long-term objectives have been to rapidly advance the state-of-the-art and diversify the applications of CubeSats according to a roadmap through the systematic use of ESA studies, R&D activities and IOD missions funded by ESA programs. Strategic pillars have focused on fostering the utility of CubeSats for LEO constellations, close proximity operations, and lunar/interplanetary missions. Roger is the chair of the Inter-Directorate CubeSat Working Group to coordinate CubeSat-related matters within the Agency, as well as the point of contact with European CubeSat industry & research institutions. His acts as Technical Chair of the CubeSat Workshop at the Small Satellite Systems & Services (4S) Symposium, and convener of the ESA CubeSat Industry Days.

Conference Abstracts

K.1 Role of small missions in Planetary and Earth Exploration

Charles Elachi

(California Institute of Technology)

Over the last decade, small spacecraft started to play a significant role in Earth and Planetary exploration, complementing the traditional large missions. This trend will accelerate driven by advances in microelectronics, lightweight materials, deployable structures, efficient power conversion and availability of low cost launch opportunities. This talk will give a number of examples of past and future missions and discuss the role these missions can play as well as the challenges that need to be addressed and overcome.

K.2 Overview of ESA Lunar and Interplanetary CubeSat Missions

Roger Walker
(European Space Agency)

The first truly low-cost lunar and deep space missions based on the CubeSat standard form factor have been flown successfully during recent years with Mars, Moon and Asteroids as destinations. These groundbreaking missions have served as pathfinders to demonstrate their potential use as tools for addressing space science and exploration objectives in a cost-effective manner, either as an augmentation to larger missions or as stand-alone missions. The hazards of operating in the deep space environment, as well as demanding requirements on propulsion, power generation, thermal control, communication and navigation capabilities have driven the development and qualification of new miniaturized technologies that are mission-enabling. At ESA, numerous lunar and deep space CubeSat projects are ongoing in various stages of design, development and verification within the frame of the Technology and Space Safety Programs, targeted for launch in the 2024-2027 timeframe. An overview of these missions will be provided, along with their system capabilities and enabling technologies underpinning their feasibility. The topic of qualification of the CubeSat COTS electronics for the deep space environment will also be addressed.

A.1 BioSentinel Deep Space CubeSat Mission

Andres Dono, Jose Alvarellos, Matt Napoli, Philip Shih, Marcie Smith, Jesse Fusco
(NASA Ames Research Center)

The BioSentinel mission was recently launched aboard the SLS launch vehicle (LV) as part of the Artemis-1 campaign. This 6U CubeSat carries yeast cells to analyze the effects of radiation at large distances from Earth, becoming the first biological payload in Deep Space. Prelaunch activities included mission design updates, orbit determination rehearsals and the development of a tracking schedule in coordination with the Artemis-1 payload office and the Deep Space Network (DSN). An important influence on the trajectories of Artemis I secondaries was the uncertainty associated with deployment from the Interim Cryogenic Propulsion System (ICPS), the upper stage of the SLS LV. The ICPS was rotating at a rate of 1 rpm; there was also uncertainty in the spin axis attitude, which translated into an unknown clock angle of deployment. The variability in this angle and magnitude of deployment implied the existence of a non-negligible risk of a lunar impact, which was evaluated for various potential launch dates.

On November 16th 2022 BioSentinel successfully deployed from ICPS and the navigation team started to receive tracking data from the DSN and ESA antennas. Soon after deployment, the spacecraft was tumbling and entered safe mode. The mission team recovered the spacecraft and after four tracking passes, we solved for a first ephemeris that was sent to the DSN for better tracking of the spacecraft. After propagating this first ephemeris solution, we determined that we avoided impact with a margin of a few hundred km from the lunar surface. More tracking data over the next few days allowed for a more refined orbit solution predicting a periselene altitude of 406 km and a lunar eclipse lasting 36.5 minutes. Therefore, BioSentinel operators avoided any correction maneuvers on the trajectory and successfully tracked and guide the spacecraft.

The spacecraft performed a nominal lunar flyby which provided the pertinent energy to achieve a final Earth-trailing heliocentric orbit. Over the course of two weeks, the mission operators corroborated that the subsystems were functioning as expected after the lunar eclipse and the large ΔV incurred. Science operations started once the mission achieved the nominal orbit in Deep Space.

This paper discusses in detail the BioSentinel flight performance, as well as the challenges and lessons learned prior to and during this CubeSat mission.

A.2 LunaH-Map: Early Operations, Science Data and Technology Demonstrations

Craig Hardgrove,
(Arizona State University)

The launch of the Space Launch System (SLS) Artemis-1 on November 16th, 2022 at 6:47:44 UTC (1:47:44 EST). brought 10 new interplanetary cubesats into cis-lunar space and heliocentric orbit. Prior to launch, each of these missions developed and demonstrated new technologies that will be useful for small and large spacecraft for planetary exploration. After deployment from SLS, radio signals and/or telemetry were received from seven of the ten cubesats, with four of those (EQUULEUS, BioSentinel, ArgoMoon and LunaH-Map) demonstrating successful capabilities for reliable telemetry and commanding. Each of these four spacecraft has now demonstrated new technologies in cis-lunar and heliocentric space. These interplanetary cubesats now join MarCO and LICIACube as the first to successfully operate in deep-space and demonstrate the value of a continued investment in these new, very small types of spacecraft and missions. Here we present the status of the LunaH-Map mission, as well as the science and technology demonstration data collected so far.

The primary science goal of the LunaH-Map mission is to spatially resolve hydrogen enrichments to tens of centimeters depth across the lunar South Pole. LunaH-Map carries a 2U neutron spectrometer, which can measure epithermal neutrons that scatter and leak from the Moon's upper meter of regolith. After LunaH-Map successfully deployed from the SLS Orion Stage Adapter (OSA) 5 and a half hours after launch, signals from the radio were measured by the Deep Space Network (DSN) Open Loop Receiver at 8:07AM EST on November 16th. The Mission Operations Center (MOC) established contact at 9:40AM Eastern on Nov 16th and successfully transitioned the spacecraft out of beacon mode. Telemetry indicated that most subsystems were responding nominally, the spacecraft was in a low momentum state, and was power positive with solar arrays tracking the Sun. Telemetry indicated the LunaH-Map spacecraft batteries were charged to 70% upon deployment. The propulsion system was, however, unable to achieve ignition. Preliminary telemetry from the propulsion system indicates this is likely from a stuck valve due to extended storage of the spacecraft of more than 1 year. Momentum is being currently being managed on the spacecraft via attitude changes and solar pressure. If the propulsion system is unable to achieve ignition, the spacecraft will continue on a ballistic heliocentric orbit with a close approach to the Earth-Moon system occurring in 2039.

Shortly after deployment on Nov 17th, LunaH-Map's Miniature Neutron Spectrometer (Mini-NS) was powered on and collected a five-minute commissioning dataset, which was used to assess the health and safety of the instrument. Beginning at 8:40 UTC on Nov 21st, 2022, a lunar flyby dataset was acquired with the Mini-NS starting at a lunar distance of 10 lunar radii from the Moon. The closest approach to the lunar surface occurred at 15:30 UTC on Nov 21st, 2022. Measurements were acquired at altitudes of 28,000, 16,000, 8,000, and 1,300 km on approach and again on departure. The raw data from a single sensor head show that neutron count rates increased by a factor of 10 between measurements acquired at 8,000 km altitude and 1,300 km altitude. This flyby dataset demonstrates that the Mini-NS can detect neutrons and gamma-rays in the lunar environment, can accomplish the originally planned LunaH-Map science mission, and is TRL-9.

LunaH-Map has developed and demonstrated several new technologies for small spacecraft. On Dec. 2nd LunaH-Map successfully imaged Mars and Uranus, demonstrating autonomous optical navigation software routines. In the coming months, LunaH-Map will also attempt a demonstration of a new type of radio ranging technique called Pseudo Noise Differential One Way Ranging (PN DOR). This would be a first-time demonstration of PN DOR and will enable better-ranging accuracy on future deep space CubeSats as well as larger missions.

A.3 CAPSTONE: A Summary of a Highly Successful Mission in the Cislunar Environment

Thomas Gardner
(Advanced Space)

NASA, Advanced Space, Terran Orbital, Rocket Lab, Stellar Exploration, JPL, the Space Dynamics Lab, and Tethers Unlimited have partnered to successfully develop, launch, and operate the Cislunar Autonomous Positioning System Technology Operations and Navigation Experiment (CAPSTONE) mission, which is serving as a pathfinder for Near Rectilinear Halo Orbit (NHRO) operations around the Moon. This low-cost, high-value mission has demonstrated an efficient, low-energy orbital transfer to the Moon and a successful insertion into the NRHO. The NHRO is the intended orbit for NASA's Gateway lunar orbital platform. The mission is now demonstrating the operations within the NRHO that ultimately will serve to reduce risk and validate key exploration operations and technologies required for the future success of NASA's lunar exploration plans, including the planned human return to the lunar surface.

Launched on June 28, 2022, by a three stage Rocket Lab Electron rocket, and utilizing a highly capable 12U CubeSat and currently, CAPSTONE has been successfully operating in the NRHO since November 13, 2022. The CAPSTONE spacecraft has recently performed its 6th Orbit Maintenance Maneuver (OMM) to maintain the baseline NRHO. Additionally, the spacecraft has successfully performed 4 CAPS technology ranging communications passes in collaboration with the Lunar Reconnaissance Orbiter (LRO) team at NASA's Goddard Space Flight Center to demonstrate the CAPS autonomous navigation system. The CAPS software enables cislunar missions to manage their navigation functions themselves and reduces the reliance on Earth based systems. Success criteria achieved thus far for CAPSTONE include 1) semi-autonomous operations and orbital maintenance of a spacecraft in an NRHO, 2) collection of inter-spacecraft ranging data in support of the autonomous navigation process, and 3) execution of the CAPS navigation software in an autonomous mode on-board the CAPSTONE spacecraft. Additionally, CAPSTONE has demonstrated an innovative one-way ranging navigation approach utilizing a Chip Scale Atomic Clock (CSAC) in combination with autonomous navigation algorithms developed by JPL.

This high value mission has already demonstrated an efficient low energy orbital transfer to the NRHO and has demonstrated full-scale operations in this unique orbit for the past 11 months. Over the next 12+ months, CAPSTONE will continue to validate these key operations and navigation technologies required for the success of NASA's lunar exploration plans. This presentation will include an overview of the current mission status, lessons learned from the launch, transfer, and insertion into the NRHO, a summary of the challenges encountered thus far, and an overview of the successful mission operations technology demonstration to date.

A.4 Taking pictures in Deep Space: ArgoMoon and LICIACube

Emilio Fazzoletto, Gianmarco Reverberi, Valerio Di Tana, Alessandro Balossino
(Argotec)

The year 2022 marked significant milestones in space exploration, with the successful launch of the Artemis-1 mission and the first planetary defense mission, DART. On board these missions were two 6U CubeSat satellites, ArgoMoon and LICIACube, equipped with high-resolution cameras designed to witness key moments of these missions. ArgoMoon and LICIACube, two missions sponsored and coordinated by the Italian Space Agency and designed and operated by Argotec, were operated correctly in deep space and captured significant pictures of key phases of the mission, including more than 600 pictures of the aftermath of the impact of DART with Dimorphos. Both satellites utilized the Hawk-6 platform, a microsat developed by Argotec with technologies suitable for deep space missions. The Hawk-6 platform incorporates advanced technologies such as radiation-hardened components, advanced solar cells, and a robust attitude control system, enabling the platform to withstand harsh conditions in deep space. Additionally, the platform has been designed to support a wide range of scientific payloads, making it an ideal choice for missions such as ArgoMoon and LICIACube. The successful operation of ArgoMoon and LICIACube demonstrates the potential of small satellites to support deep space exploration providing additional science to big missions at a fraction of the cost. Additionally, the use of the Hawk-6 platform in these missions highlights the importance of developing specialized microsat technologies suitable for deep space missions. As the development of microsat technologies continues to advance, we can expect to see more innovative solutions that enable us to explore the cosmos in new and exciting ways.

A.5 Navigation of LICIACube: Challenges and Lessons learned

Luis Gomez, Igor Gai, Marco Lombardo, Edoardo Gramigna, Marco Zannoni
(Department of Industrial Engineering, Alma Mater Studiorum – Università di Bologna)

Recently, the advances in science instruments and spacecraft miniaturization technologies pushed the CubeSats beyond their typical low Earth orbit applications. The deep space represents the new frontier for the SmallSats, either as stand-alone missions, or as companions to larger missions on which they could "catch a ride" to the most remote and challenging destinations in the Solar System.

The Light Italian Cubesat for Imaging of Asteroids, LICIACube, is a 6U CubeSat mission of the Italian Space Agency (ASI), developed and operated by the Italian company Argotec, under ASI coordination and with the contribution of several Italian Research Institutions. LICIACube participated in the NASA's planetary defense DART mission, which tested the effectiveness of kinetic deflectors by impacting into the secondary asteroid of the Didymos system, Dimorphos. LICIACube provided unique pictures of the post-impact scene, acquired during a single high-speed flyby of the Didymos asteroid system, supporting the energy exchange investigations.

On September 11, 2022, the CubeSat was released from the DART piggyback dispenser and started its independent approach to the system. Few hours later, the navigation operations of LICIACube kicked-off. For the following 15 days, different orbital and desaturation maneuvers were designed and executed, leading LICIACube towards the predefined location to observe DART's impact on Dimorphos. On September 26, 2022, about 168 seconds after DART's impact, LICIACube flew by the asteroid at ~58 km and ~6.1 km/sec, capturing images of the impact, the ejecta plume and the non sun-lit side of Dimorphos, becoming the first CubeSat to flyby an asteroid in deep space. After the impact, the spacecraft continued on its trajectory while downloading the acquired images to the Mission Control Centre until December 23, 2022, when following an ASI decision, the spacecraft was commanded to execute the end-of-life procedure, and subsequently the end of mission was declared.

The navigation strategy of LICIACube relied on classical two-way radiometric data, range and range-rate observables, and has been performed independently by both the University of Bologna (UNIBO) and the JPL. This work discusses the navigation processes performed by the UNIBO flight dynamics team in order to support efficient and accurate navigation operations. In addition, it covers the challenges and the lessons learned on deep space CubeSat navigation.

A.6 A DSN Retrospective on CubeSat Support for Lunar Flashlight

Kristofer Buckmaster, Kris Angkasa
(Jet Propulsion Laboratory, California Institute of Technology)

NASA's Deep Space Network (DSN) provides space communications services that include initial acquisition, tracking, telemetry, command, and delivery of science & mission status data over terrestrial links to mission operation centers. This presentation will provide a DSN Mission Interface Manager's perspective on the successes, challenges, and lessons-learned from provisioning DSN Services for the Lunar Flashlight mission - a 6U Cubesat spacecraft demonstrating the use of green propulsion to reach the Moon, and equipped with near-infrared lasers to search for water ice deposits in the shaded polar regions. The Lunar Flashlight project is managed by the Jet Propulsion Laboratory, in partnership with the Georgia Institute of Technology for Mission Operations support.

A.7 Highly accurate surface propagation for Mars Helicopter mission.

Nacer Chahat, Gaurangi Gupta, Matthew Chase, Courtney Duncan
(Jet Propulsion Laboratory, California Institute of Technology)

NASA's Jet Propulsion Laboratory has developed the first Mars helicopter: Mars Ingenuity. The helicopter has the capability to transmit to and receive data from a Mars Rover located at a distance ranging up to 1 kilometer. The antenna designs and propagation on the Mars surface will be addressed in this talk. After multiple successful flights, our team collected enough data to compare the accuracy of our models accounting for shadowing effect, multipath, polarization loss, and fading.

Ingenuity was originally slated to operate for 30 days on Mars, conducting a technology-demonstrating mission designed to test whether or not powered, controlled flight is possible on Mars. However, with the overwhelming success of its first flights, NASA has decided to extend the helicopter mission and shift it into a new phase where it will act as a scout for the Rover. It has been operating on Mars for more than a year. This came with numerous challenges - with one of the biggest being the telecommunication link prediction in adverse communication scenarios with complex surface topology and non-line-of-sight (NLOS) scenarios. Our team at the Jet Propulsion Laboratory developed and demonstrated a highly accurate link budget prediction using the Parabolic Equation method taking into account the actual surface topology of Mars. It was verified using 14 flight cases before being entirely infused into the mission operation tools to plan each flight of the helicopter to ensure this asset will not be lost on the surface of Mars.

A.8 Downsizing Mission Design for CubeSats

Daniel Grebow
(Nabla Zero Labs)

More than half of the ten CubeSats that were launched with Artemis 1 encountered mission jeopardizing problems. The Artemis 1 CubeSat campaign serves as a powerful demonstration that the risk of mission failure for CubeSats is significantly greater than what we are normally willing to tolerate for space missions. Still, CubeSat missions are relatively inexpensive compared to their larger-scale counterparts, and with the success of interplanetary CubeSats like MarCO, we now feel more comfortable flying more ambitious CubeSat missions. The risk of loss for these missions is well worth the investment in the case that the mission proves successful.

CubeSat missions however present a rather thorny problem for mission designers. While there is a significant cost savings building these spacecraft, the astrodynamics does not scale proportionally—trajectories are indifferent to the size of the spacecraft. In fact, one could argue that the mission design for CubeSats is more challenging than for larger-scale missions. Generally, CubeSat missions do not have designated launches and therefore must follow on a whim the launch targets of the prime mission. For the Artemis 1 CubeSats this was particularly challenging. Depending on lunar phasing, the reference trajectory from one launch day to the next could be totally different. Cubesat propulsion systems also perform less well than conventional propulsion systems, making it more important for mission designers to design trajectories that conserve propellant. Furthermore, CubeSat spacecraft have a greater chance of experiencing post-launch anomalies which typically translates to more work for mission design, sometimes necessitating an entire re-design of the mission.

Despite these challenges, we believe it is imperative to find ways to downsize mission design for CubeSats. The reason for this need is precisely because these missions are intended to be significantly cheaper. It runs contrary to this principle if in the end more work is required to fly a CubeSat mission. Simply put, we believe CubeSat mission design should tolerate more risk and be prepared to adapt to changes during operations.

In this talk we will present several risks that mission design should be more willing to accept and why ultimately descoping mission design will make these missions feasible in the future. Our talk comes from several years of experience in working on CubeSat mission design, particularly for the NEAScout and Lunar Flashlight missions.

B.1 Inflatable reflector antenna for CubeSats: CATSAT mission and Cis-Lunar system design

Aman Chandra
(FreeFall)

CATSAT is a 6U CubeSat mission to demonstrate inflatable antenna technology in Low Earth Orbit. The mission is in collaboration between the University of Arizona and FreeFall Aerospace, Inc based in Tucson, Arizona. Our work presents updates to the CATSAT mission, having been delivered for launch and awaiting flight later this year. We discuss planned LEO mission operations and spaceflight qualification tests done to prove and deliver the inflatable antenna system. Further developments to the inflatable antenna system are presented. These include an on-orbit rigidization system for the inflatable membrane and the incorporation of a beam steering system. These developments have led to inflatable antennas being studied for more complex mission architectures. On-going work on the next generation inflatable antenna system based on a 12U platform is presented in the context of Cis-Lunar and xGEO applications.

B.2 Tree of Life: Tree-Mounted Antenna and Accessible Ground Station

Charles Penny, Alessandra Babuscia
(Jet Propulsion Laboratory, California Institute of Technology)

The Tree of Life is a mission which ultimately aims to demonstrate mission longevity through use of a CubeSat in low-Earth orbit coupled with ground stations on Earth based around trees. Data on the trees and from the CubeSat would be used to serve art and science goals. One of the principal intentions of the project is for it to be widely accessible to audiences of different experience levels so that they may participate in the collection and use of data. To further this project, an accessible way for participants to receive data from the proposed satellite in low Earth orbit at the tree was needed. Previously demonstrated was the use of a loop antenna mounted on a tree trunk or branch to estimate the dielectric properties of the tree, and consequently make inferences about the physiological state of the tree. Here, we further explored the use of this tree mounted antenna as part of a receiving station for data packets from satellites in low-Earth orbit. We designed a low cost and flexible ground station composed primarily of commercially available components or parts which can be made without significant overhead or resources. The tree-mounted antenna was integrated into this system in a variety of configurations, including single and multi-antenna versions. In testing with existing satellites in low-Earth orbit, downlink was successfully achieved. That said, the performance of the system was not competitive with other existing receiving station that do not have to contend with being mounted onto a tree and attenuation that such an environment causes. So, in the niche applications where the receiving
station must be physically very close to a tree, this solution does make some sense. However, for reliability a more traditional ground station would behave more consistently. In the context of the Tree of Life mission, this solution is considered to be a valid secondary form of data downlink, especially for crowdsourced operators with limited resources.

B.3 CubeSAT Deep Space X-Band TT&C Transponder (C-DST)

Giovanni Cucinella*, Andrea Negri*, Lorenzo Simone**, Pier Luigi De Rubeis**, Giuseppe Piscopiello***, Paolo Tortora****

*(*IMT srl, **Thales Alenia Space Italia, ***Sitael SPA, **** Interdepartmental Center for Industrial Research in Aerospace (CIRI-AERO))*

In recent years, there has been a clear trend of space mission projects to include planetary small spacecraft (e.g., CubeSats) that fly as secondary payloads, and are deployed at destinations to perform missions and communicate via the main spacecraft or direct to Earth. The added value for planetary science and exploration is twofold: (a) enhance primary science objectives; (b) enable new science and exploration in new, potentially dangerous environments. Furthermore, these small companion missions can be an excellent platform for testing novel technology demonstrators.

In addition, science investigators are usually more inclined to accept higher risk by exploring dangerous/unknown environments using relatively low-cost platforms.

A key element of deep space missions is the communication system, which needs to be DSN/ESTRACK compatible, small, light, and not power-hungry. Such a unit does not exist in Europe, at the moment. Bearing in mind JPL's IRIS unit as a benchmark, we preliminarily proposed to ESA, in mid- 2019, our technical solution prepared by a consortium (IMT srl, Thales Alenia Space Italy, Sitael and CIRI Aerospace of University of Bologna) which brings together all necessary know-how and expertise in the field of CubeSat and SmallSat technologies, digital and analog RF TT&C systems, power systems, radio science experiments.

The Contract with ESA was signed by IMT, as Prime Contractor, on sept. 2019, To be destinated to LUMIO and M-ARGO missions (both from ESA)

This paper describes the results gained so far in the design and development of the Model to be validated/qualified in view of two main ESA missions, LUMIO and M-ARGO.

In summary, the C-DST includes three assemblies:

- Main Assembly: for main functions of the unit, both DIGITAL and RF. It is composed of four modules (RX, TX, DIGITAL, Power). The Main assembly is powered by the unregulated satellite bus and it is connected to the OBC through the digital interfaces (discrete lines, CAN bus for TM/TC data, and RS422 for Payload data). In addition, internal interfaces ensure the power and data connections with the LNA assembly and HPA assembly.
- LNA Assembly: it provides the LNA chains. The assembly can accommodate up to 3 antenna input ports, and it can be located close to the antenna (to improve the RF performances) or in-stack with the Main Assembly.
- HPA Assembly: composed of the power conditioning and the SSPA modules. The SSPA module could accommodate up to 3 SSPA chains with 3 different antenna ports.

B.4 First In-Flight Demonstration of Psuedo-Noise Delta-Differential One-Way Ranging

Christopher P. Volk, Zaid J. Towfic, James S. Border, Mazen M. Shihabi
(Jet Propulsion Laboratory, California Institute of Technology)

Spacecraft requiring high-precision deep-space navigation use Differential One-way Ranging (DOR) tone signals to perform DDOR measurements. So far, these DOR tones are narrowband signals which differ greatly from the broadband quasar signals used in Delta-DOR (DDOR) measurements. This introduces a potential leading error term into the DDOR error budget. For the next-generation deep-space missions, which require higher precision measurements, this potential error can be reduced by transforming the narrowband spacecraft signals to broadband spacecraft signals. Recent CubeSat missions to the moon have launched with the latest Iris CubeSat Deep Space Transponder firmware capable of modulating the narrowband DOR tones with a pseudo-noise (PN) spread spectrum Gold Code sequence. Use of these PN spread spectrum signals during DDOR are referred to as PN DDOR. This paper reports on the initial results from these lunar CubeSats, including the operational impact of PN DDOR, the received waveform qualities at the Deep Space Network (DSN), and the resulting PN DDOR performance.

B.5 A Commercial Lunar Surface S-Band User Terminal

Faramaz Davarian*, Mazen Shihabi*, Matt Chase*, Emmanuel Decrossas*, John Baker*, Stuart Golden**, Kevin Lynaugh**

*(*Jet Propulsion Laboratory, California Institute of Technology, **Vulcan Wireless)*

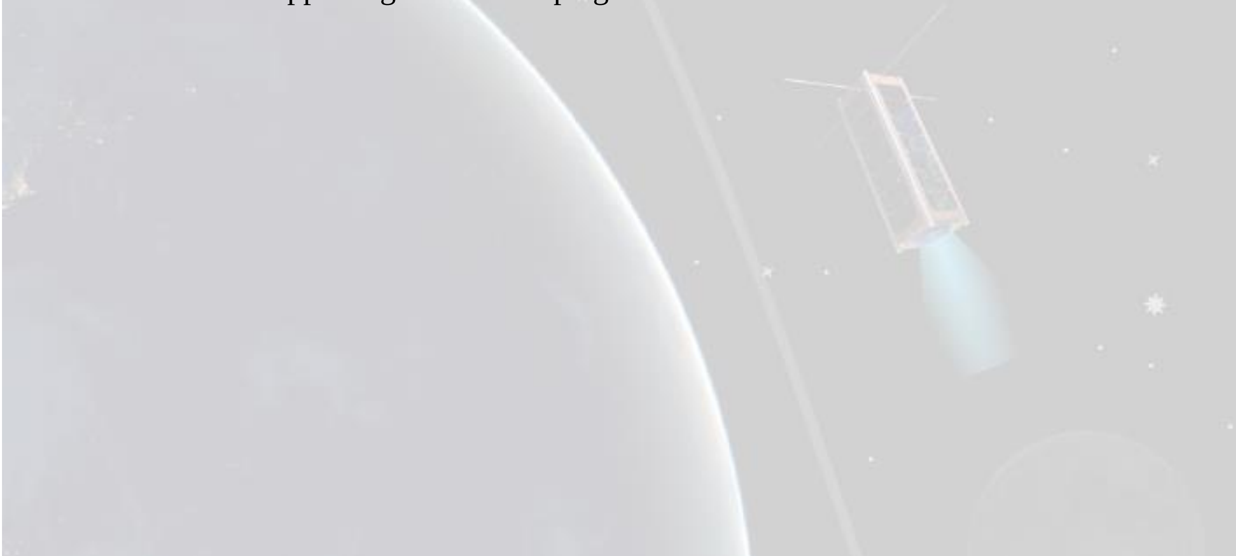
The current decade will witness a great rise in human and robotic lunar exploration that will include both scientific endeavors and commercial interests with many nations participating. Much attention will be focused on the far side of the Moon. In order to support these lunar exploration opportunities, a robust communication network, consisting of ground stations, lunar relay satellites, and surface user terminals, is required which is low in cost and can meet the increasing communications needs of the lunar explorers. This paper focuses on a user terminal (UT) solution that is being developed to meet the Size Weight and Power (SWaP) needs of the future Commercial Lunar Payload Services (CLPS) lunar landers and payloads.

The JPL surface UT consists of an S-Band Software Defined Radio (SDR), one S-Band Antenna and an 8x1 Data Switch that supports Ethernet or serial interfaces to provide communication connectivity for multiple on-board commercial and scientific payloads. That is, the UT will enable the payloads to concentrate on their perspective missions without having to design the communication system. The UT's design elements include radiation-tolerant, temperature tolerance, and Doppler correction to enable these lunar missions. The immediate purpose of the surface UT is to commission relay operation of the Lunar Pathfinder relay satellite that is being built by Surrey Satellite Technology Limited (SSTL), institute a new CCSDS communication protocol for S-Band Proximity-1 based on the successfully used Mars relay operations, and establish space heritage. This modification of the standard based protocol is a multinational effort designed to enable and simplify orbital surface payload communications at the Moon. The UT is being developed by Vulcan Wireless, a JPL subcontractor, and NASA is funding the development. Vulcan Wireless is selling the radios commercially.

B.6 Simultaneous Tracking and Navigation Solution for 8 CubeSats using the DSN's Open Loop Receiver

Daniel Kahan, Walid Majid, Dustin Buccino, Clement Lee, Oscar Yang, Meegyeong Paik, Elias Barbinis, Gerhard Kruizinga, Shan Malhotra, Douglas Abraham
(Jet Propulsion Laboratory, California Institute of Technology)

On 2022, November 15-17, the JPL Radio Science team collaborated with the Artemis Campaign Navigation team in support of 8 CubeSats (ArgoMoon (ARGO), BioSentinel (BIOS), CubeSat for Solar Particles (CuSP), EQUULEUS (EQUL), LunaH-Map (HMAP), Lunar IceCube (MLIC), NEA Scout (NEAS), and Omotenashi (OMOT)) released during the launch of the Artemis mission to the moon. Due to the insufficient number of transmitters and tracking receivers at the Deep Space Network, as well as the desire to optimize the amount of tracking time for all CubeSats, the Interferometric Narrowband Spacecraft (INS) method was used to compute a navigation solution for each spacecraft. The INS method differences the received carrier frequency measurements from two concurrently tracking DSN complexes in order to remove the oscillator drift on each spacecraft. Using this technique, all eight assets were to be tracked simultaneously at two overlapping complexes, for a total of 16 elements to monitor at once. The event covered 4 overlapping periods, spanning a total of 30 hours in duration. Doppler data were recorded on the DSN's Open Loop Receivers (OLRs), which unlike the DSN's primary tracking receivers, capture a broad spectrum and can be tuned to multiple sources so long as they remain within the antenna beam. Data were transferred to JPL in near real-time, processed to Doppler observables, filtered for data quality, and converted to Tracking Data Messages (TDM)s, a standard navigation input product. The navigation team then utilized the INS method to compute a navigation solution for each spacecraft. While the Radio Science operators monitored acquisition of signals on the OLRs, most processing and delivery steps were completed with automation tools. Ultimately, four of the eight CubeSats (ARGO, BIOS, EQUL, and HMAP) were successfully detected and went on with their missions; three (CuSP, MLIC, and OMOT) were successfully tracked during deployment but discontinued communications thereafter; and one (NEAS) was never detected. Data capture with the OLR for use with the INS method proved valuable as a means for establishing the ephemerides for multiple CubeSats deployed at once. The suite of automation tools developed for this event will be valuable for supporting similar campaigns in the future.



B.7 Status of the Interplanetary Network for the Space Internet

Jose Velazco
(Chascii Inc.)

Chascii was founded with the specific goal of providing ubiquitous superfast, low-latency connectivity along the solar system through the deployment of its commercial INterplanetary SPace InteRnEt (INSPIRE) network. INSPIRE seeks to deploy a large number of small spacecraft (smallsats), arranged as autonomous swarms, to create optically interconnected network nodes around planetary bodies and their Lagrange points. It is envisioned that future scientific and commercial space missions can use INSPIRE as their low-latency fast-data-rate connectivity provider. The deployment of Chascii's INSPIRE network will start with its cislunar subnetwork. The cislunar INSPIRE network includes nodes in GEO and Earth-Moon Lagrange points 1 and 2 to create a secure and covert network for space users. A key innovation of INSPIRE is the use of swarms of smallsats as network nodes. These swarms behave and operate like a much larger and costlier spacecraft. Each INSPIRE ship will be a unique 12U smallsat equipped with six optical transceivers featuring full-sky coverage and capable of gigabit per second data rates. It will be able to communicate with other spacecraft from the INSPIRE network as well as with ground assets. Chascii is developing critical technologies to enable INSPIRE including intersatellite optical communicators, RF/Optical ground stations, and associated software. In this paper we will discuss the latest design status of the INSPIRE swarms including their optical terminals for short- and long-range connectivity.

B.8 Snapdragon Initiative & Common Instrument Electronics

Andre Jongeling, Zaid Towfic, Doug Sheldon
(Jet Propulsion Laboratory, California Institute of Technology)

Two investment activities at the Jet Propulsion Laboratory have worked in partnership to produce a powerful processing platform targeted for use in future small sat missions.

The JPL Common Instrument Electronics (CIE) task is an investment activity aimed at developing a flexible instrument controller that can be used in a broad range of applications and a wide set of instruments and missions. The Swift Processor is the primary product of the CIE task and is designed to be highly adaptable to various applications. It is based on the Xilinx Kintex Ultrascale (KU060) FPGA and makes use of two mezzanine slots inspired by the industry standard FPGA Mezzanine Card (FMC) interface.

The JPL Snapdragon Initiative followed the success of the Mars Ingenuity helicopter in a collaboration with Qualcomm to produce the Snapdragon Co-Processor (SCP). The SCP is based on the Qualcomm SA8155P SoC and is designed to provide a flexible and robust ultra-high performance (> 7 TOPS) computing platform for a wide range of missions and instruments.

The SCP is designed as a mezzanine card of the CIE Swift Processor which can hosts one or two SCP mezzanines.

Each of these developments is of interest individually but together they form a powerful processing platform that enables a revolutionary boost in onboard computational power required for the future of robotic space exploration.

Both of these platforms are currently assessed at Technology Readiness Level 5 (TRL5). An overview of these platforms will be provided as well as plans for reaching an assessment of TLR6 in the near future.

C.1 Validation and Utilization of Deep Space Station 17: A University-Operated Affiliated Node on the NASA Deep Space Network for Interplanetary Small Satellite Missions

Benjamin Malphrus*, Chloe Hart*, Jay Wyatt**, Tim Pham**
*(*Morehead State University, **Jet Propulsion Laboratory, California Institute of Technology)*

Small Satellites, particularly CubeSats, are facilitating a new era of lunar and interplanetary exploration. The extremely successful Mars (MarCo) mission in 2018 was followed by the Artemis 1 lunar missions (Lunar IceCube, LunaH-Map, and CAPSTONE) and asteroid explorer (NEAScout) in 2022. Numerous other interplanetary SmallSat missions are being planned by NASA, ESA, JAXA and commercial ventures. All of these activities require ground support for communications, navigation and tracking- support that requires significant infrastructure including ground stations with large apertures, full-motion antennas and specialized deep space ranging and telecommunication instrumentation. With an already high demand on mission support, the DSN, even with the expansion of the new antennas and with the implementation of new techniques to increase the antenna utilization (i.e., multiple spacecraft per aperture), will be challenged accommodate the large number of missions expected as the SmallSat revolution unfolds. To begin to address this challenge, partnership between JPL and Morehead State University was initiated in 2014 to enhance DSN capabilities by utilizing existing non-NASA assets. The idea is that an enhanced DSN can be achieved by transferring DSN processes and techniques, precision timing standards, data formatting, handling and transfer protocol, and mission and ground operation processes to existing university-based large aperture antennas. The team used the Morehead State University 21 m Space Tracking Antenna as a case-study to prove the validity of the concept. The goal of this project has been to develop and implement a strategy to transfer DSN processes and protocol to the MSU 21 m antenna system to enable integration into the DSN as an auxiliary station to support small-sat missions. The program focused on the implementation of DSN capabilities with deep space communication and navigation tracking techniques, including Space-link Extension (SLE) protocol and CCSDS data standardization, and asset scheduling capabilities. The upgraded station, designated DSS-17, came into service in 2022. DSS-17 is also serving as a pilot ground station for emerging technologies with the potential to substantially lower CubeSat mission cost and risk, or even enable new types of deep space missions to be proposed. These new capabilities include Disruption Tolerant Networking (DTN), spacecraft-initiated operations utilizing a beacon tone service, and Opportunistic Multiple Spacecraft per Aperture (OMSPA). DTN operations will be validated for use on CubeSats through ground testing with DSS-17, JPL DSN nodes and the European Space Agency DTN nodes in an upcoming experiment. An overview of DSS-17 will be provided emphasizing empirical validation data, principally from CAPSTONE, to illustrate DSS-17's utility for lunar communications and navigation.

C.2 Multiple Uplinks Per Antenna (MUPA): Potential Communication and Navigation Benefits for Smallsats

Douglas S. Abraham, Shakeh E. Brys, Matthew D. Chase, Shantanu Malhotra, Leila Meshkat, David D. Morabito, James A. O'Dea, Emily R. Pascua, Marc Sanchez-Net, Dong K. Shin, Zaid Towfic

(Jet Propulsion Laboratory, California Institute of Technology)

NASA's Artemis-1 secondary cubesats faced a unique challenge in endeavoring to deploy from the Orion stage adapter on the Interim Cryogenic Propulsion Stage (ICPS): having enough ground antennas available to provide all 8 DSN-supported cubesats with adequate 2-way Doppler and ranging, as well as communications. With only 3-to-4 DSN 34m antennas available at the in-view Complex and at least two of those required by Artemis-1 itself, there simply were not enough antennas to go around. To help on the downlink, a technique known as Multiple Spacecraft Per Antenna (MSPA) was applied to up to four smallsats at a time. MSPA enables multiple in-beam spacecraft to simultaneously downlink to individually assigned receivers through a single ground antenna. Unfortunately, they cannot currently do the same on the uplink. Each of the participating spacecraft has to uplink one at a time with a 10-to-30-minute reconfiguration period between each uplink. Hence, the amount of time each participating spacecraft has available for commanding and 2-way Doppler and ranging is extremely limited and inversely proportional to the number of participating spacecraft in the MSPA session. To "wring" greater utility out of the DSN's antennas in this and other cases where multiple spacecraft are all in-beam together (e.g., Mars, Venus, in-beam constellations, localized lunar surface assets, etc.), the participating spacecraft need to be able to simultaneously uplink through the same antenna with which they are downlinking during the MSPA session.

To this end, NASA and JPL have been exploring the potential implementation of a Multiple Uplinks Per Antenna (MUPA) technique. In this technique, Forward Communications Link Transmission Units (FCLTUs) comprising the command streams emanating from each participating Mission Operations Center (MOC) are multiplexed onto a single uplink frequency that is then radiated from the antenna participating in the MSPA session. All of the associated spacecraft receive this uplink, recover the transfer frames associated with each FCLTU, differentiate their intended transfer frames from those destined for other spacecraft on the basis of spacecraft ID, and then recover their intended commands or data. In addition, because all the participating spacecraft are locked to the single uplink carrier from the outset, they can all simultaneously perform 2-way Doppler over the entire pass duration. Efforts to date have focused on prototyping an FCLTU multiplexer, pathfinding the implementation "hurdles" within the DSN's systems, and, within the Iris radio, emplacing the variable turnaround ratios and onboard Doppler compensation needed to make MUPA work. The next steps involve ground and flight demonstrations of these capabilities with smallsat missions.

C.3 NASA Deep Space Network (DSN) Experiences with Artemis-I Cubesat Mission Support

Stephen M. Lichten, Douglas S. Abraham
(Jet Propulsion Laboratory, California Institute of Technology)

The Deep Space Network (DSN), operated by JPL for NASA, initially provided tracking and communications support for 8 of the 10 cubesats that were deployed during the Artemis-I launch in November 16, 2022. While the DSN had previously successfully supported deep space cubesats, Artemis-I cubesat support presented unique challenges due to several special circumstances, including the fact that so many spacecraft were deployed and requiring DSN support simultaneously, at the same time that the DSN was providing prime tracking and communications coverage for the Artemis-I mission. In the subsequent weeks, 2 additional cubesats, not initially supported by the DSN, also requested DSN support. Collectively, the Artemis-I cubesats made greater than expected demands on the DSN, in part because they experienced numerous unexpected spacecraft emergencies and safe modes. The Artemis-I cubesat experience required the DSN to employ a number of "spacecraft rescue" techniques that are available, but infrequently exercised. While the overall cubesat mission success rate for these deep space Artemis-I cubesats was low in the end, the DSN successfully deployed and demonstrated a number of new and innovative techniques for their support. The DSN and NASA experience with Artemis-I cubesats will be discussed in this presentation, along with some lessons learned and plans for DSN support of future deep space cubesat missions.

C.4 OMSPA Deployment in the DSN

Jason Liao, Clayton Okino, Shan Malhotra
(Jet Propulsion Laboratory, California Institute of Technology)

The era of Interplanetary Small Satellites is causing ground station congestion. All of these CubeSat activities require significant infrastructure with large aperture antennas for deep space telecommunication. With high demand on mission support, the Deep Space Network (DSN) is looking into techniques to increase the antenna utilization for the larger set of missions. The Opportunistic Multiple Spacecraft Per Antenna (OMSPA) project performs open-loop recording of another spacecraft in the antenna beam of a primary spacecraft track and uses a software receiver to demodulate and decode the recorded telemetry signal in near real-time. Telemetry frames are made available using existing offline Space-Link Extension (SLE) protocol typically in 4 but no more than 24 hours. OMSPA makes use of a fully automated scheduling process to provide additional software downlink channels using the current DSN infrastructure. Recent Artemis 1 CubeSat activities provided ample processing and testing opportunities with up to 8 spacecrafts in the antenna beam. An overview of the OMSPA project, status, and benefits will be provided.

C.5 Deep Space Network Small Sat Data Management

Sirina Nabhan
(Jet Propulsion Laboratory, California Institute of Technology)

The JPL Project Data Systems Engineering (PDSE) team within the Telemetry, Tracking, and Command (TTC) group in the Deep Space Network (DSN) went through a rigorous campaign of integrating and training for cubesat payloads of the Artemis I mission. The DSN is the sole data link provider of TTC services for over forty missions traveling to the moon and beyond. In the past ten years, the number of operational spacecrafts has doubled. In addition, Phase D missions are integrated into the network by a rigorous compatibility test campaign which lasts six months to one year which comes with their own scheduling needs. The launch of Artemis I includes thirteen cubesats fighting for limited resources. Artemis II will also have several cubesat payloads. Additionally, the growth of New Space companies presents the DSN with customers who have less experience using DSN tools.

Integrating several cubesat missions demanded training material specific to cubesat customers. this cause the PDSE to develop new data process to account for low budge spacecraft missions. Efforts to reduce demand on operator attentions starts with being informed about data management methods such as follow-the-sun, Opportunistic Multiple Spacecrafts Per Antenna (OMSPA), and Space Link Extension (SLE) upgrades. Data delivery from one mission to the next can be dynamic and standardizing services for incoming cubesat missions will ensure the support of the influx of small sat payloads.

C.6 Progress Towards a Large Aperture Antenna in New Zealand for Deep Space Telecommunications

Robin G. McNeill
(Space Operations New Zealand Ltd)

Incumbent New Zealand telco, Spark, has for 12 years been leasing a redundant 30 metre aperture, full-motion, C-Band antenna at its Warkworth Satellite Earth Station to Auckland University of Technology (AUT) for radio astronomy purposes. AUT had designed and built an interchangeable X-Band feed to augment frequency coverage and installed a hydrogen-maser clock.

Last year Space Operations New Zealand (SpaceOps NZ) was invited to take over the AUT operation after the university decided to abandon its radio astronomy interests.

SpaceOps NZ has agreement in principle with all parties to operate the antenna, subject to a number of conditions, including a successful survey of the antenna and beam-waveguide components, an electromagnetic interference analysis and evaluation of the antenna’s suitability for S-Band operation. These are in hand. A nominal S-Band feed has been designed to assist analysis, and a desktop study undertaken to establish compatibility with SpaceOps NZ’s scheduler, which had been designed for low Earth orbit multi-antenna multi-mission operations. Spacecraft signal testing in conjunction with JPL is being planned.

Progress to date is promising to meet the intention of supporting deep space missions and to avail the antenna for radio astronomy purposes. All going well, SpaceOps NZ will take over operation of the antenna on 1st July 2023. A high-data rate modem and ancillary equipment is planned to be installed later in the year, with the antenna to become commercially available in early 2024.

C.7 A multi-mission solution for meeting the mission control needs of CubeSat missions

Leila Meshkat
(Jet Propulsion Laboratory, California Institute of Technology)

Small spacecraft and satellites, or CubeSats, are increasingly being built and operated by NASA and its partners. Such missions help to reduce the cost of new space missions and enable new architectures for a wide range of activities in space. Similar to all space missions, CubeSat missions require a mission control system to support real-time monitoring and control of the spacecraft (both pre-launch and post-launch), including downlink telemetry processing and display as well as preparation and initiation of the transmission of spacecraft commands through the ground-space telecommunications networks. But because of the differences in scale and performance associated with CubeSat missions, the infrastructure required for satisfying these needs is unique. The NASA level Multimission Ground Systems and Services (MGSS) program is currently developing the infrastructure required for a multi-mission mission control system for CubeSat missions. This talk will elaborate on the unique mission control needs for CubeSat missions and discuss the current work in progress by MGSS to create a multi-mission control system for these mission types.

C.8 Improving Small Spacecraft Mission Operations in Deep Space through the use of Disruption Tolerant Networking and Spacecraft-Initiated Operations

E. Jay Wyatt*, Marc Sanchez Net*, Nathaniel Richard*, Benjamin Malphrus**, Emily Walter**, Nathan Fite**

*(*Jet Propulsion Laboratory, California Institute of Technology, **Morehead State University)*

Small spacecraft missions in deep space are inherently different in many ways than traditional larger-scale deep space missions. They can be lower priority when competing for scarce communication resources, have less redundancy, simpler fault protection systems, less funding for operations, less experienced operations teams, and unproven mission enabling technologies, to name a few. Moreover, the forward looking mission landscape for small spacecraft missions is unique. Small spacecraft, for example, can be used to create constellations, fleets, and contribute to large-scale Lunar exploration in the coming decade. For these and other reasons, deep space small spacecraft missions can be considered novel within the worldwide space community. What is not novel, however, is the strong tendency to operate these missions in much the same way as flagship missions or similar larger mission classes. It generally isn't well known, however, that there are highly mature capabilities that can be used to create operations concepts better suited for small spacecraft. These capabilities can lower mission risk, increase science return, improve operational efficiency, or lower mission operations cost. Moreover, if adopted, space agencies worldwide over time can operate more effectively and improve our collective ability to explore the Solar System. Two of these capabilities will be described. The first is Space Networking. Just as the internet has become pervasive on Earth, the space-based analog to the terrestrial internet can allow missions (even single missions) to be operated more effectively, enable networked spacecraft mission concepts, enable coordinated observations between two or more spacecraft, and improve automation for space-based relays. Space networking enables interoperability among spacecraft, which means that each spacecraft launched can become a node of the solar system internet. Over time, this can create a permanent communication infrastructure in space by adding communications redundancy, improved performance, and decreased mission lifecycle cost. The other capability to be discussed is Spacecraft-initiated Operations. With this approach, pre-planned communication periods can be largely eliminated for most mission phases and a more adaptive means of communicating adopted. The spacecraft determines when to communicate and signals the ground system and mission operations team to activate when telemetry downlink or command uplink is required. These capabilities are largely available today, flight validated, and especially suited to small spacecraft missions. This briefing will describe how these technologies work, specific capabilities and services that are currently available, mission use-cases, and overall benefits for deep space small spacecraft missions.

D.1 The HERA Milani Mission

Margherita Cardi*, Marco Pavoni*, Daniele Calvi*, Franco Perez Lissi**, Paolo Martino**, Ian Carnelli**

*(*Tyvak International Srl,**European Space Agency)*

Hera is the European part of the Asteroid Impact & Deflection Assessment (AIDA) international collaboration with NASA who is responsible for the DART (Double Asteroid Redirection Test) kinetic impactor spacecraft. Hera will be launched in October 2024 and will arrive at Didymos in January 2027. The Hera mothercraft will accommodate two 6U cubesat, Milani and Juventas. The Milani cubesat is developed by Tyvak International leading a consortium of European Universities, Research Centers and Firms from Italy, Czech Republic, Finland. During the cruise to the Asteroid (+2 years), Milani CubeSat will be hosted inside the Hera mothercraft, periodically checked for health and charged. At arrival it will be deployed and commissioned while HERA is performing the Didymos detailed characterization phase, at about 10 to 20 km distance from the asteroid. The Milani mission objectives are defined as to add scientific value to the overall Hera mission: i) Map the global composition of the Didymos asteroids, ii) Characterize the surface of the Didymos asteroids, iii) Evaluate DART impacts effects on Didymos asteroids and support gravity field determination, iv) Characterize dust clouds around the Didymos asteroid, enhancing the scientific return of the whole HERA mission. The scientific payloads supporting the achievement of these objectives are the main Payload “ASPECT” (developed by VTT, Finland), a SWIR, NIR and VIS imaging spectrometer and the secondary Payload “VISTA” (developed by INAF, Italy), a thermogravimeter aiming at collecting and characterizing volatiles and dust particles below 10μm.

The Milani mission and the project team is facing challenges such as, among others, the use of COTS components in deep space environment, optical navigation implementation, interfaces management with the HERA mothercraft since the very beginning of the design up to the mission. Tyvak International work focuses on the development and integration of the Milani CubeSat platform, including mission specifics development enabling the mission and vehicle models enabling early interface testing with Hera mothercraft.

D.2 Exploring the Solar System with Cubesats: New Missions from Argotec

Valerio Di Tana, Gianmarco Reverberi, Emilio Fazzoletto, Alessandro Balossino
(Argotec)

In recent years, there has been a growing interest in using small satellites, particularly CubeSats, for deep space exploration. Despite some setbacks, it is now possible to envision challenging missions for studying the solar system using these platforms. Argotec, in collaboration with the European Space Agency (ESA) and the Italian Space Agency (ASI), is working on two new science missions aimed at studying the Moon and space weather. The Lunar Meteoroid Impact Observer (LUMIO) mission, led by Politecnico di Milano, is designed to refine our understanding of the lunar meteoroid environment and demonstrate CubeSat technologies in the lunar environment. LUMIO will be equipped with an optical payload that will detect impact flashes of meteoroids. The mission will be carried out in an Earth-Moon L2 HALO orbit, allowing for continuous observations of the lunar surface. The data collected by LUMIO will contribute to the development of models for the lunar meteoroid environment and inform future lunar exploration missions. The High Energy Neutral particle detector ON Hawk (HENON) mission is a pathfinder mission that will explore the Distant Retrograde Orbit (DRO) for space weather operations and science. HENON aims to provide real-time monitoring of the deep space environment beyond L1, providing alerts for solar energetic particle events and geoeffective interplanetary perturbations. The mission will also contribute to our understanding of heliophysics through the collection of scientific data. Both missions will be equipped with advanced technologies for deep space, including rad-hard avionics systems, and will be deployed on the 12U Hawk platform. These missions represent a significant step forward in terms of ambition for science missions using small satellites. Both missions will push the boundaries of what is currently possible with CubeSat technology, and will be important milestones for the utilization of small satellites in deep space exploration. Furthermore, the missions will provide valuable data that will inform future lunar exploration missions and enhance our understanding of space weather and heliophysics.

D.3 The Tree of Life: A Project of the Space Song Foundation

Julia Christensen*, Steve Matousek**

*(*Oberlin College, **Jet Propulsion Laboratory, California Institute of Technology)*

The Tree of Life is the primary project of the Space Song Foundation, a non-profit founded by artists and scientists to promote long-term thinking at the intersection of art, science, and design– on Earth, and in outer space. The Tree of Life began with the premise that we must transcend current frames of technological obsolescence in order to build spacecraft that can possibly complete a mission to an interstellar destination, such as Proxima B. Meanwhile, we need to think past obsolescence to communicate with such interplanetary technology over decades or centuries, as well as to create sustainable conditions on Earth. The Tree of Life tackles the challenge of building both Earthbound and space-borne technology that can operate for 200 years as a means of working towards a future interstellar mission, while expanding the notion of longevity in the public cultural sphere.

The Tree of Life is a public art & science project that includes a CubeSat deployed in low-Earth orbit for 200 years, during which time it will transmit data about its operational status to a series of terrestrial trees that have been augmented to act as living, Earthly antenna. At the site of the trees, simultaneously, a 200-year dataset describes the tree’s health and environmental conditions. The data points collected in space and on Earth are translated into audible sonic frequencies that can be transmitted via radio between the trees and CubeSat, so that effectively, the trees and the spacecraft can sing together in a 200-year duet. This “song” will be made available online for the public to study, sample, and remix, and the tree sites will be presented as public sonic artworks.

At the ISSC, Space Song Foundation President Julia Christensen and Board Chair Steve Matousek will present about the art, science, and design behind the Tree of Life project.

D.4 Autonomous Small Spacecraft Rendezvous and Docking via Adversarial Reinforcement Learning

Connor Fuhrman, Jekan Thangavelautham
(Space and Terrestrial Robotic Exploration (SpaceTREx) Laboratory, University of Arizona)

Robust and fully autonomous rendezvous and docking (AR&D) is a driving capability for extended deep space operations. The 2020 NASA Technology Taxonomy calls for "[r]endezvous and docking algorithms [which] are independent of gravity fields and provide more robust and flexible software […] to address a wider range of future missions that require AR&D". Such missions will require autonomous rendezvous with target objects ranging from man-made to orbital debris to primitive celestial bodies necessitating autonomous control algorithms which dynamically react using onboard sensing. Particularly, missions which utilize a marsupial-like architecture in which a larger "mothership" transports, deploys, and reacquires "child" crafts, e.g., for sample acquisition of ejected particles from a rubble pile asteroid or for asteroid belt exploration, fully depend on AR&D to recover any deployed child crafts.

Reinforcement Learning (RL) based approaches for AR&D have shown promising results. However, many RL-based techniques fail to generalize because (1) the "sim to real" gap where the simulation fails to accurately model the real-world, or (2) data scarcity. Both problems are exacerbated for applications in space as precise environmental simulations may be impossible and simulating all potential environments is infeasible.

This work presents an AR&D control algorithm developed using Adversarial Reinforcement Learning (AdRL). In AdRL the primary agent is trained whilst an adversarial agent introduces disturbances - such disturbances can be viewed as representing the error between the simulated environment and the real world. AdRL has been shown to improve training stability, be robust to differences in training and testing conditions, and to outperform the baseline policy even without the adversary.

The primary agent is a 6-DOF CubeSat which autonomously performs AR&D. The observation space consists of its own kinematic state and relative kinematics about the other craft and the action space determines thrust commands. Sensing capabilities sufficient to gain observations are assumed as relative navigation systems are mature. The adversarial agent may apply linear and angular forces to the primary agent. The training procedure is two-fold - the adversarial policy is fixed and the primary policy is learned, then the primary policy is fixed and the adversarial policy is learned, then the process repeats until convergence. We will train an RL-based and AdRL-based agent in the same environment and compare both model's generalizability to various environmental scenarios. We expect the AdRL-trained agent to be more robust, flexible, and generalizable to perturbations in gravity fields between AR&D scenarios used for testing.

D.5 Radar tomography of small asteroids with cubesat platformesat platfrom

Alain Herique, Wlodek Kofman
(Université Grenoble Alpes)

The Hera/ESA mission will be launched in 2024 to rendezvous in 2027 the Near Erath Asteroid 65803 Didymos binary system. Dimorphos, the Didymos moonlet, was the target of the DART impactor NASA Mission last September. HERA will deeply investigate the binary system and especially the DART crater on Dimorphos, increasing the science return of the DART mission. After rendezvous, HERA will deliver two CubeSats, Milani and Juventas, for close observation during two months of both Dimorphos and Didymos down to less than 1 kilometer distance. Juventas is a 6U CubeSat carrying JuRa, a low frequency radar operating in monostatic mode. JuRa will provide the first direct measurement of an asteroid's internal structure probing two small bodies. It is associated with a gravimeter and an Inter Satellite Link to access the gravity field.

The DROID (Distributed Radar Observations of Interior Distributions) mission is proposed to rendezvous Asteroid 99942 Apophis in 2029, a potentially dangerous asteroid which will then approach Earth as close as 32000 kilometers. The mission concept has been developed in a collaboration between NASA/JPL and CNES: the DROID mothership will arrive months prior to Earth closest approach proving crucial optical observations to monitor any induced tidal response. After Earth-closed approach, it will release two CubeSats which will orbit Apophis for several weeks. These two 6-8U CubeSats will offer a unique opportunity to directly observe the Apophis internal structure with a Bistatic Low Frequency Radar associated to the gravity field measurements from the Inter Satellite Link.

The knowledge of the asteroid's internal structure is crucial to better understand its accretion and dynamical evolution, to study its stability conditions and to model its response to the gravitational constraints induced by Earth close approach. This is also crucial to plan any interaction with an asteroid especially for Planetary Defense purposes. While our present knowledge entirely relies on inferences from optical remote sensing observations and theoretical modeling, the Radar is one of the most mature technique to providing a direct measurement of the internal structure.

CubeSat platforms are especially relevant for both bistatic and monostatic radar offering measurement at low altitude associated with a large diversity of geometry of observation. In this talk will present the concept and status of the two missions in association with the question of the radar tomography.

D.6 PoZoLE, the Polarized Zodiacal Light Experiment: an Astrophysics Pioneers Cubesat for mapping our zodiacal dust to help see other Earths against their own dust clouds

Neal Turner*, Greg Holsclaw**, Sally Haselschwardt**, Evan Bauch**, Farbod Khoshnoud***, Brita Olson***, Zahra Sotoudeh***, Susan Terebey****

*(*Jet Propulsion Laboratory, California Institute of Technology, **CU/LASP, ***Calpoly Pomona, ****CSULA)*

The Polarized Zodiacal Light Experiment (PoZoLE) has two science objectives: (1) Determine what our zodiacal cloud looks like from a distance, in the near-UV waveband where NASA's flagship Habitable Worlds Observatory will one day search against analogous exozodiacal backgrounds for the Hartley absorption band of ozone in the atmospheres of candidate exo-Earths. (2) Determine how much of our zodiacal cloud's near-UV brightness comes from dust shed by (a) main-belt asteroids, (b) short-period comets, and (c) Oort Cloud comets. Engineering and science students from underrepresented groups at regional universities help develop and operate the spacecraft, and analyze and interpret the data.

PoZoLE measures our zodiacal cloud's shape and size from LEO, determining the distribution of material along the line of sight using the fact that the sunlight scattered from interplanetary dust is most-polarized when deflected ~90°. PoZoLE's 55-mm-aperture telescope mounted in a 6U CubeSat maps the zodiacal light's polarization in fields along the ecliptic and up to the poles. The coverage and precision enable determining the cloud's size and shape, as we demonstrate by synthetically observing radiative transfer models of the cloud and recovering the models' input parameters. The cloud's shape is governed by the component particles' orbital inclinations, so measuring the shape enables distinguishing asteroidal from short-period cometary sources and determining whether Oort Cloud comets contribute a nearly-spherically-symmetric component. Galactic and extragalactic backgrounds are well-subtracted when modeled fields at a set of Sun-centered ecliptic coordinates are observed repeatedly over the 6-month baseline mission.

PoZoLE is implemented by early- and mid-career professionals mentored by experienced staff at JPL and LASP. The project uses high-heritage designs with no technology development, and simple and flexible operations, while carrying 20% cost reserves.

NASA's Habitable Worlds Observatory will target UV wavelengths for high angular resolution and for sensitivity to one of the strongest signatures of an oxygen atmosphere, ozone's Hartley band. This band must be sought against the bright background of the host star's light scattered from the exozodiacal dust near the planet. PoZoLE measures the shape and size of the only such cloud whose structure we can relate to the orbits of its parent comets and asteroids: our own zodiacal cloud. Our cloud's appearance is wavelength-dependent, yet few measurements exist in the UV, a gap PoZoLE closes to quantify a risk facing the future Observatory. The project provides experience with spacecraft, instruments, mission operations, and space astronomy to students from minority-serving institutions.

D.7 Evaluation of deployable Telescopes for Small Satellites on Asteroid Recon Missions

Hilliard Paige, Javier Alday, Quinn Lamey, Matthew Walton, Jared Pavek, Sergey Shkarayev and Jekan Thanga

(University of Arizona)

Detection of near earth asteroids (NEA) has become increasingly important for scientific and planetary defense applications. Currently most NEA detection is conducted with ground-based telescopes due to cost and logistical constraints. However, these stations can be limiting due to atmospheric disturbances, light pollution, and increasing amounts of space debris in orbit. In this work, we propose an orbiting deployable telescope for asteroid reconnaissance. The optical elements are packaged into a CubeSat for efficiency. This technology would fill a capability gap in detecting NEAs with very low albedo. The objective of the project is to demonstrates the capability to detect NEA's approximately 0.3AU from earth with albedos between 0.05 and 0.1 for scientific and planetary defense applications. This work also aims to demonstrate tensegrity inspired mechanical deployment technologies in volume constrained structures, maximizing both aperture and focal length.

The proposed telescope integrates into a standard 12U CubeSat bus, of which 8U are reserved for the tensegrity telescope payload. Sizing of the optics was synthesized from requirements on sensing the physical parameters and location of the NEA's mentioned above. A 6-inch Schmidt-Cassegrain primary mirror was selected due to its low cost and ease of integration with our mechanical design. The secondary mirror was replaced by a HyperStar lens from Starizona which allows the sensor to be mounted where the secondary mirror would be. This gives the system a F/2 ratio with a focal length of 300mm. A tensegrity inspired design was developed based on a 2-stage deployable structure with rods in compression counteracted by servo actuated strings in tension. Alignment of the optics is achieved through control algorithms prototyped on a raspberry pi single board computer. The mechanical design thus far has been an iterative process with special attention was paid to static and dynamic load considerations during launch and deployment of the system.

The results have shown the feasibility of tensegrity inspired deployable structures while maintaining accuracy for optical alignment. If needed, the capability of realignment has been demonstrated. Recent work has seen the prototype validate the optical requirements through earth-based simulation with similar conditions expected in space. Mechanical requirements have been validated through deployment testing, and the alignment of the optics have been demonstrated.

D.8 The SpaceTREx Story: Ten Years of Research and Development Advancing the Small Spacecraft Paradigm

Jekan Thangavelautham
(Space and Terrestrial Robotic Exploration (SpaceTREx) Laboratory, University of Arizona)

The Space and Terrestrial Robotic Exploration (SpaceTREx) Laboratory started in the state of Arizona back in 2013. The laboratory was founded to utilize engineering-science principles in conceptualizing, designing and developing ground-breaking small spacecraft missions and technologies. The lab as part of its core mission has been training the next generation of aerospace engineers and scientists for Arizona. The laboratory has counted on government agencies and labs as its major sponsors. The lab has witnessed solid growth year after year mirroring the rise of small space and Newspace industries producing more than 270 technical publications and presentations, 10 provisional and full patents and wining over $17 million in research and development contracts. Steady growth also brought challenges including administrative pressures to be on specific space missions that would stretch lab resources beyond technical feasibility, to administering laboratory space to meet specialized needs of a space program.

Ultimately, the laboratory shed administrative pressures and had followed an independent path striving to meet sponsor expectations, with honesty, excellence and long-term vision towards advancing transformative and disruptive potential of small spacecraft. A second major challenge has been dealing with the TRL Valley of Death and the lack of paths to success for many potential/revolutionary space technologies. SpaceTREx has pursued pathways to infuse technologies it has developed through collaboration with government agencies and private industry. The team also faced numerous logistical challenges along the way, some that have inspired new research investigations while others that have resulted in down-scaling certain research thrusts. Propulsion is one such research that faced severe difficulties, primarily because of the challenges of a university environment in supporting and nurturing research that has high-standards of safety, security and inherent challenges.

Growth at the laboratory has been reinforced by ever increasing market demands for aerospace engineering and planetary science students. The laboratory has matriculated more than 150 students, mostly undergraduate, with nearly 16 Master's students and 3PhDs. Graduates estimated to be about 70% are finding jobs in the aerospace and defense industry, while others are finding positions in robotics, IT and auto industry. The accomplishments made in the SpaceTREx laboratory was used to jump-start ASTEROIDS Laboratory under NASA funding in 2020. ASTEROIDS aims to tackle some of persistent challenges in aerospace, namely lack of gender and ethnic diversity and to strengthen America's aerospace workforce. The team developed an innovative Undergraduate Research and Education Program to advance opportunities for undergrads through space research and facilitate interest in education.

The program has produced numerous success stories from underrepresented groups going onto to do great things. Importantly, the program has cultivated wide interest in space exploration, space development and space technology and services in Southern Arizona.

E.1 Pelican: Radiation-tolerant Computational Storage

Alex Swehla, Jason Cerundolo, Alex Hiam,
(Zephyr Computing Systems)

Pelican is a radiation-tolerant, high-capacity solid state drive designed for spacecraft by Zephyr Computing Systems. This storage device provides high-capacity data storage through the use of 3D-NAND technology and a custom flash controller implementation. Pelican is designed from the ground up to mitigate the adverse effects of radiation while providing high performance with low Size, Weight, and Power (SWaP). The core electrical hardware, including the FPGA and power system, is radiation-tolerant and suitable for Earth orbit and cis-lunar missions with a path towards further hardening for inter-planetary missions. In addition, Pelican provides onboard compute resources with both general purpose and AI-enabled processors attached to the flash memory to accelerate IO intensive workloads by co-locating them with the storage. This allows for the generation of data products on the storage device itself, reducing processing time and effectively increasing the bandwidth between Pelican and a host device. The complete storage device simplifies integration by using the industry standard form factor, PC104. The primary data interface is Non-volatile Memory Express (NVMe) protocol over a Peripheral Component Interconnect Express (PCIe) Interface, though it will be possible to customize this as needed. Storage capacity in the first version will be at least 2 TB of usable space. This is not raw capacity, but instead accounts for the redundancy and over-provisioning required to meet reliability requirements. Future versions of the product will increase the capacity to 6 TB and beyond. Sequential reads and write speeds support modern Earth observation workloads with 2,000 and 1,000 MB/s respectively, and random operations in the range of 10,000 to 30,000 IOPS. Pelican will enable new science missions, particularly those requiring capturing and managing large amount of data, facilitate onboard AI/ML processing, and support terrain relative navigation and proximity operations.

E.2 Radioisotopic Propulsion for Small Satellites

Jeremiah Pate
(Lunasonde, Inc.)

This paper describes a novel magnetoplasmadynamic thruster where a direct energy conversion method is used to efficiently harness a radioisotopic energy source into useable thrust. An alpha emitter both ionizes and heats a gaseous propellant transforming it in a hot plasma. A magnetic nozzle is then used to convert this hot plasma into a cold plasma with collimated ion trajectories to generate beam power and thus ultimately thrust. This simple yet low loss approach allows to efficiencies surpassing 80%, and a low mass system. Conventional MPD thrusters suffer from large masses and power requirements. This is a consequence of the numerous power conversion stages from an onboard power source (whether solar or nuclear) into beam power. This is effectively curbed by the proposed system since this thruster does not require a Brayton cycle system to electric power to ionization to beam power chain of conversion. All the previously mentioned steps are replaced by the simple conversion of energy from the alpha emitter source to plasma thermal energy. As the full system is self-contained and low mass, this means of propulsion has the potential to enable low mass spacecraft to reach delta v ranges >10 km/s.

E.3 FD04 Frangibolt Actuator Performance Test: Measuring Force and Stroke Margin

Ingie Baho, Kim Aaron
(Jet Propulsion Laboratory, California Institute of Technology)

A new approach for measuring force and stroke margins for Frangibolt actuators has been developed and is described in this paper. Frangibolt actuators, which are sold by Ensign-Bickford Aerospace & Defense Company (EBAD), are widely used across the Aerospace industry as hold-down and release mechanisms (HDRMs). They are comprised of a resistance heater which warms a piece of shape memory alloy (SMA). The heat induces a phase change in the SMA, which grows in length enough to break a notched fastener, thereby releasing the bolted joint. The SunRISE project uses FD04 Frangibolt actuators to release deployable antennas. The SMA alloy in this line of actuators is formed from a single crystal of Copper, Nickel, and Aluminum. This particular alloy exhibits a greater expansion than the more traditional FC series of multi-crystal Titanium-Nickel alloy. In our initial exploratory testing with the FD04, we followed the same testing approach others have used to test FC series Frangibolt actuators, but the behavior was sufficiently different that we consulted with EBAD. As a result of that discussion, we understood that the test procedure used on the FC series Frangibolt was not applicable to the FD04, and that led us to develop a new testing methodology. The novelty of this test procedure is that an initial pre-load is applied to the Frangibolt which simulates the load a torqued bolt in a flight assembly would apply. Due the difference in nature of the crystals in the SMA, this pre-load application was not needed for the FC Frangibolt series. After the pre-load is applied, our FD04 Frangibolt is actuated, and the load it experiences linearly increases to the desired test load. The stroke of the Frangibolt was measured at each test load using an extensometer. The force and stroke needed to break the bolt are 643 lbf and 0.0079 in, respectively, which were calculated from data provided by EBAD. In this paper, we explain the novel features of our test method and the nuanced differences between our method and that which was used for the FC Frangibolt series. Details of our test results are also provided which ultimately verify that the FD04 Frangibolt demonstrates more than enough force and stroke to break the notched Frangibolt fastener: 1286 lbf and 0.0193 in on average, respectively.

E.4 Ultrathin carbon nanotube freestanding thin films with specular reflective coatings for small satellites

Ho-Ting Tung, Evy Haynes
(UCLA)

Growth of small satellite interplanetary missions necessitates development of novel lightweight deployable materials and systems. Among these high quality reflective thin films are of great interest for thermal control (radiators), deployable antennas, inflatable and deployable telescope components, and radiation pressure attitude control systems. In this work we study ultrathin (~1μm) carbon nanotube (CNT) freestanding thin films with optically smooth reflective coatings. Thin film CNTs exhibit unique properties including high thermal conductivity, heat resistivity, plasma resilience, while being a lightweight material (~1g/m2). Typically fabricated carbon nanotube films are not optically smooth and lead to excessive light scattering, which limits their functionality. Here we demonstrate an approach with the use of a smooth sacrificial layer. Our fabricated free-standing films are optically smooth and <1 micron thick, enabling ultralight <1g/m2 secularly reflective films. Several different metal coatings, including Al, Pt and TiN are explored. Thermal stability tests show that films can survive >400 C. As an example use of our films we consider a solar sail material that is capable of reaching close to the sun. Such solar sails can enable fast transit small satellite interplanetary missions.

E.5 Martian Lava Tube Exploration with Aerial Delivery Vehicle

Anna Dinkel, Kylar Nietzel, Roman Anthis, Nicholas Mammana, Elijah Greenfield, Andrew Frisch, Jekan Thangavelautham, Sergey Shkarayev
(Department of Aerospace and Mechanical Engineering, University of Arizona)

Lava tubes on Mars provide insight into Martian geography and may be critical for future manned missions. In volcanic regions of Mars, lava flows clear out these large pristine caverns. As the tubes provide stabilization and protection from the Martian surface atmosphere and environment, they may be the key to developing human shelters on Mars. There are over 1,000 potential lava tubes in the Tharsis Mons volcanic region of Mars. These detected lava tubes have large skylight entrances formed by collapsed ceilings, where the ground below is filled with rocky debris. This presents a mobility concern entering the skylight without damaging the environment and passing over the rough terrain to get to the lava tube.

We propose a solar balloon for surface travel that houses and lowers an inflatable wheeled rover designed for traversing challenging subterrain. Martian wind currents propel the solar balloon, and propellers provide directional control. It is powered using a solar panel skin and rechargeable batteries. The solar balloon hovers over a skylight entrance and lowers a rover to explore the lava tubes via a tether spool system. The rover carries instrumentation that collects a 3D point map and photographic images to characterize the environment of the lava tube. It deploys an antenna relay communication system that transmits data between the rover and the solar balloon.

In this paper, we will discuss the details of our proposed design of a solar balloon and inflatable rover system. We perform comparisons of various aerial components, instrumentation, and guidance and control devices. We analyze a simulation of the communication relay. We discuss the initial testing procedure, and results of the rover lowering mechanism and navigation in an applicable environment. We also identify shortcomings of our research and discuss future research and testing.

E.6 Laser-based Localization of Robot Swarms for Lunar Infrastructure Construction Using Control Towers

Min Seok Kang, Sivaperuman Muniyasamy, Jekan Thangavelautham

(Space and Terrestrial Robotic Exploration (SpaceTREx) Laboratory, University of Arizona)

NASA’s Artemis program aims to restart crewed missions to the moon. This program may lead to semi-permanent human settlements on the lunar surface. Before the arrival of humans, robots can prepare the infrastructure for a long-term base on the moon. They can also take over the dirty, dull, and dangerous tasks, reducing the personnel necessary to support science missions on the moon. Using multiple rovers in a swarm increases the efficiency of operations such as infrastructure construction and support. However, in the early stages of lunar base development, the infrastructure for the navigation and communication of such robots is limited, with difficulties in supporting large swarms of rovers.

We propose a design for control towers to support a swarm of infrastructure construction robots. These towers will provide communications, navigation, and power beaming using lasers. The advantage of using lasers is that the same hardware can handle communications links, precise positioning, and wireless power transfer instead of using different dedicated systems.

For lunar rover communication and positioning, we examine the possibility of using laser communications using a “smart skin.” Previously, we have proposed utilizing a “smart skin” containing solar panels for laser communication with and between small satellites. Current commercially available solar panels for space vehicles can detect violet and blue lasers, even in daylight, making them viable options for sensors in laser communications. Using existing solar cells as sensors can reduce costs compared to installing receivers in each rover for radio navigation and communications.

We attempt to apply communications using lasers and solar panels to find the precise positions of individual rovers in a swarm on the moon. Laser communications and positioning will allow more effective rover cooperativity and situational awareness. Our proposed method also aims to reduce the cost of installing sensors and infrastructure for communication and positioning.

E.7 Space Debris Remediation: Modeling of a Particle Cloud Momentum Interceptor

Jared Bartunek, CJ Jauregui, Marcos Marcucci-Rodriguez, Rick Loehr, Greg Ogden
(University of Arizona)

Space debris, also known as orbital debris, is defined as any man-made object in orbit about the Earth that is no longer being used or serving any function. Debris falls into three distinct categories; rocket bodies or stages, abandoned or defunct satellites, and fragmentation debris. Depending on the orbit and altitude, the debris will not naturally deorbit for several years to several centuries posing a substantial risk. This debris can impact operational projects resulting in the damage to or the loss of a project and the likely addition of new fragmentation debris. As the overall space object mass grows each year, the density of such can become high enough that one collision can generate a cascade of further collisions, thus generating a cloud of debris completely surrounding the Earth. This effect is known as Kessler syndrome and would make future space activities impossible. As interest in space operations grows in both the government and private sectors, the risks that debris poses are substantial and require a n immediate solution. The solution we propose is Active Debris Removal (ADR) or space debris remediation via a material cloud of particles. This method aims to remove potentially damaging man-made objects from vital orbits. We propose a two-stage rocket that intercepts and de-orbits the desired object by deploying a Particle Cloud Momentum Interceptor (PCMI) in its path. The concept of operations (Con-Ops) is as follows: A. A large piece of debris is identified as having a possible conjunction with another large object. The debris' trajectory is tracked and modeled to predict a launch window. B. The first stage uses a Solid Rocket Motor (SRM) to launch the PCMI payload through the atmospheric phase. The first stage is reusable and will fall into the ocean where it will be retrieved. C. The second stage is then engaged to position the PCMI payload so that it may intercept the debris' trajectory. D. The PCMI is then deployed, strategically spraying a material cloud in the path of the debris. E. The PCMI interacts with the space debris and slows it down without immediate damage. F. The debris loses sufficient momentum after the interaction, changing its orbital dynamics. It will then de-orbit due to increased contact and friction with the atmosphere. This paper first examines the feasibility of such a system by conducting a review of previous work and conducting estimate calculations. Then progressing into modeling the following: the quantity and density of the particles necessary to achieve this de-orbiting, the parameters for the PCMI's pathway at the requested altitude, the generation of the PCMI itself, the thermodynamics of the interaction between the PCMI and the debris, and the trajectory of both the debris and the two-stage rocket. The modeling of the cloud is done by assessing the environmental conditions of Low Earth Orbit (LEO), the material specifications of the debris and the particle cloud, and previous corresponding papers to ensure a safe, successful interaction. This data is then utilized by particle cloud modeling software and trajectory software to output the theoretical cloud requirements based on the targeted debris. The modeling of the trajectories is done through numerical propagators in MATLAB. By creating a force balance and solving for the velocity and acceleration, we can accurately model the rocket's launch trajectory. The debris is modeled from observational data collected by the Space Force's debris tracking. Validity testing was also conducted using Black Brant sounding rocket trajectory data. They have provided altitude and range data based on payload mass and launch elevation angle that can serve as a comparison for the trajectory simulation. Additionally, the coefficient of drag based on Mach number has been estimated using the OpenRocket software to increase the accuracy of the simulation. Current proposed solutions' costs can range in the millions of dollars, are much more complex, and can typically only remove one or two types of debris. The cost of the mission is analyzed and estimated to be significantly cheaper and has the potential to remove any type of debris.

E.8 Title Lessons Learned Developing Lunar Flashlight Flight Software using the F Prime Product Line

Aadil Rizvi, Kevin F. Ortega
(Jet Propulsion Laboratory, California Institute of Technology)

NASA's Lunar Flashlight (LF) CubeSat mission was launched on December 11th, 2022 and is on its way to the Moon. LF is a six-unit (6U) low-cost secondary payload CubeSat that will map the lunar South Pole for volatiles and demonstrate several technological firsts, including the first planetary CubeSat mission to use green propulsion, and the first mission to use lasers to look for water ice.

LF flight software is based on the open-source F Prime Flight Software Product Line developed by JPL. F Prime utilizes a reusable component-based architecture with typed ports that can be interconnected to form a topology. Also, F Prime includes a set of auto-coding tools used to generate components and topologies that can be deployed for various mission specific applications. The Sphinx C&DH board, developed at JPL with a commercialized variant provided by Cobham, is used on LF as the hardware platform for executing the software deployment. F Prime provides a highly modular and reusable framework enabling flight software development for the Sphinx avionics platform that is adapted for mission specific use on LF. This presentation provides an overview highlighting development of LF flight software, facilitated by use of the F Prime product line, along with lessons learned from the development and operation of flight software for the CubeSat mission.

F.1 Path planning and optimal trajectories for Mars sailplanes subject to stochastic atmospheric conditions

Adrien Bouskela
(University of Arizona)

The exploration of planetary bodies such as Mars conventionally targets areas with high expected scientific return which are favorable to Entry Descent and Landing technologies. Yet, areas of higher value exist outside of destinations reachable with these typical landers and rovers, leading to a growing interest in unconventional exploration platforms. The use of small spacecrafts for such interplanetary studies has been demonstrated by the Ingenuity rotorcraft, opening access to previously unreachable science objectives such as canyons, craters, and mountains with airborne vehicles. Past research has demonstrated the feasibility of unpowered sailplanes for this purpose. They overcome the energy challenges of fixed wing flight on Mars by exploiting atmospheric energy in the form of unsteady winds, which are known to exist on Mars thanks to occasional measurements and extensive modeling.

The latter has enabled large scale studies but remains insufficient in predicting the environment accurately and rapidly for the purposes of flight planning, meaning that Mars sailplanes remains a high-risk high reward solution. The present work introduces methods to reduce this mission risk with risk adverse optimal flight planning methods. Sailplanes have the capability of packaging into the CubeSat standard for reduced cost, increased number of vehicles, and possible ride sharing for atmospheric entry. The associated challenges of low Reynolds flight are addressed with an efficient blended wing body design.

Flight planning and optimal trajectories are constructed using a three degree of freedom model under stochastic atmospheric conditions. Data for which is taken from an existing data set obtained with the Mars Regional Atmospheric Modeling System (MRAMS) for a section of Valles Marineris. Stochastic modeling enables the introduction of risk quantification and minimization, building robust flight paths for an initially unknown environment. Concepts from Model Predictive Control theory are implemented, constructing navigation algorithms for autonomous optimal flight in an unsteady atmosphere without reliance on complete initial knowledge of the Martian wind environment. Flight experiments are conducted on earth at high elevations, validating theories behind atmospheric energy harvesting, and demonstrating the long endurance observed when implementing the optimal flight algorithms. Overall, providing methods to reliably and autonomously extend the mission time of aircraft destined for Mars, opening the possibility of extensive atmospheric exploration and studies of high value geological features.

F.2 Fast transit outer planet exploration with small satellites

Arthur Davoyan
(University of California, Los Angeles)

Despite a rapid progress with space exploration and advanced robotic missions, mission to outer planets and Kuiper belt objects present a significant challenge. Presently such missions take many years of flights time and decades of development, frequently costing >$1B. In our work we discuss several advanced propulsion methods that could place small CubeSat class spacecraft onto fast flyby trajectories. Specifically, we study three propulsion approaches: extreme solar sailing, laser driven sailing, and a novel concept of pellet-beam propulsion. All of these propulsion methods could allow getting to Neptune in less than a year. In the context of solar sailing we show that sails that can get close to the sun, less than 10 solar radii, can be placed onto fast exit hyperbolic trajectories. We then discuss challenges of such missions and our development of supporting technologies. Laser driven sailing can offer an alternative. In this case spacecraft is propelled with high power laser beams. For example, laser sailing is suggested for propelling small mass probes to near-speed of light velocities in the context of Breakthrough Starshot mission. We will discuss the utility of laser sailing for interplanetary flight. Finally, we will overview briefly our new NIAC concept based on laser ablation propulsion – pellet-beam propulsion, which can offer higher efficiency as compared to direct laser sailing.

F.3 Flatworm-Inspired Robot for Extraterrestrial Exploration

Rebekah Cutler, Athip Thirupathi Raj, Jekan Thangavelautham
(Space and Terrestrial Robotic Exploration (SpaceTREx) Laboratory, University of Arizona)

Robotic systems have revolutionized the way that planets are explored and analyzed. They allow extraterrestrial environments to be examined safely and remotely, and many propositions for new space robots exist. However, most of these robots are still in their infancy. Additionally, many must avoid trailing a variety of terrain. Instead, they specialize in one specific environment and are limited to it — often traveling at low speeds. This is troublesome for planets like Mars (with ice caps and desert areas) and a significant hindrance when exploring new planets with unknown physical environments. There is a need for an all-terrain explorer robot that can travel quickly to analyze the surface of various planets in a short amount of time.

We propose a robot inspired by the marine flatworm, which travels using sinusoidal-moving flaps and can adopt various configurations to traverse ice, sand, solid rock, dirt, and water. It is called the Slugbot, in reference to its locomotion. The Slugbot is inspired by the Velox robot created by Pliant Energy. It will be equipped with a high-quality camera and various sensors to capture its environment as it travels. It will be programmed to evaluate the terrain it travels through and autonomously adapt its fin positions to the configuration best suited for the physical environment. As such, the Slugbot will be a precious tool for the autonomous exploration of unexplored planets and known planets with varying terrain.

This paper discusses the design, manufacturing, testing, and further iterations of the Slugbot. It is driven by 16 high-torque servo motors connected to an Arduino microcontroller. Its shell is entirely 3D printed and is approximately 44 inches in length. The fins are made of rubber sheets and attached to the servos using pinchers. Testing will be conducted to ensure effectiveness and evaluate for necessary changes to adapt the robot to a low-gravity environment. These will include terrain tests, responsiveness tests, sensor tests, and incline tests. Finally, we will utilize the data and observations from these tests to create iteration 2 of the Slugbot - which will be miniaturized for ease of transit and weight savings, autonomous, and ready to explore extraterrestrial environments independently.

F.4 Energy Harvesting from Spacecraft Charging: An initial study using WarpX for PIC simulations

Ashwyn Sam
(Stanford University)

As a spacecraft moves through space plasma, it can develop large magnitude potentials relative to the ambient plasma due to a phenomenon called spacecraft charging. While engineers have historically tried to mitigate this effect due to negative consequences like electrical arcing and unsolicited interactions with on-board experiments and equipment, these large magnitude potentials also pose an opportunity for energy harvesting from the space environment. Orbit-motion-limited (OML) models have been used to analyze this technique, but their applicability is limited to certain plasma regimes and spacecraft geometries. To further explore this idea, this research employs the Particle-in-Cell (PIC) method. Specifically, this study aims to build computational models for the analysis of spacecraft charging using WarpX, a highly optimized 3D electromagnetic PIC code. In this paper, we present the first results of spacecraft charging analysis using WarpX. We describe the numerical algorithm in the WarpX solver and the method used to compute the electric potential on the spacecraft. As a first step for verification, we conducted a simulation of a spherical spacecraft immersed in a static uniform plasma, comparing the results against OML. We also conducted benchmark tests for a CubeSat immersed in a flowing plasma with and without magnetic field, secondary electron emission, and photoelectron emission. These initial tests aim to study the feasibility of energy harvesting from spacecraft charging using simulations. This research expands on the current understanding of spacecraft charging and its potential for energy harvesting, providing new insights into this promising technique.

F.5 A Swarm Approach for Interstellar Object Intercept Missions

Vivek Verma, Massimo Biella, Jekan Thangavelautham
(Space and Terrestrial Robotic Exploration (SpaceTREx) Laboratory, University of Arizona)

Since its detection in 2017, 1I/'Oumuamua has been categorized as the first known interstellar object (ISO) to have passed through our home solar system, shortly followed by interstellar comet 2I/Borisov. Interstellar objects are believed to be planetesimals or chunks of rock that were knocked off planetary bodies during the origination and early evolution processes of neighboring solar systems in the Milky Way. As a result, they are believed to contain a great wealth of data that could ultimately further our understanding of exoplanets and the formation of our solar system. Moreover, carrying out a mission to an interstellar body would enhance our knowledge of near-Earth asteroids (NEAs) and allow us to better develop a more efficient and ready planetary defense system.

Different metrics are derived as a function of the ISO's position and velocity while on its

hyperbolic trajectory through our solar system. The reference mission concept involves utilizing an n-size spacecraft swarm to pre-position themselves in the vicinity of the target's trajectory to ultimately be able to adjust their state and attitude to converge onto a predetermined impact site. The decision-making processes within the swam account for the separation between each spacecraft and the ISO. Based on this information, different roles are assigned to each actor of the swarm. The impactors and remote-sensing spacecraft will utilize onboard cameras and sensor suites to estimate the ISO's shape, size, and rotational velocity, along with a wide array of physical, geological, and dynamic properties. As the impactor spacecraft approaches the ISO, it will conduct an observation campaign by taking pictures up until collision.

To maximize the science throughput, a spacecraft will be employed to perform a high-speed fly-by through the cloud of plumes ejected from the impact crater. Ion Neutral or dust mass spectroscopy can be performed depending on the amount and type of sample collected. The data collected by the different actors of the swarm is finally relayed to a predetermined spacecraft that will be tasked with transmitting it back to Earth for further analysis.

F.6 Evaluating the Feasibility of Emergency Response Using Network of Small Robots on a Lunar Base

Siva Muniyasamy, Min Seok Kang, Jekan Thangavelautham
(Space and Terrestrial Robotic Exploration (SpaceTREx) Laboratory, University of Arizona)

The early stage of the lunar base helps us to understand the surface characteristics of the moon for resource prospecting, mining, and constructing next-generation space observatories. Artemis program would enable the first lunar base on the moon. We proposed in our previous papers that the smart sensors and distributed computing architecture integrated with a network of robots support the day-to-day operations of the lunar base. The network of robots will do dull, dirty, and dangerous tasks so that astronauts can focus on priority science and exploration tasks. The tasks included asset management, cleaning, repair, maintenance, and handling emergency scenarios and to name a few tasks. The emergency scenarios, such as accumulation of smoke, fire, and toxic chemical residue that humans would otherwise not sense. Modeling the emergency scenarios is significant for evaluating the condition and performing tasks that are necessary to handle the situation effectively rather than abandoning the base and evacuating the astronauts. In this paper, we focus on one of the disaster events-fire and model the fire using distributed computing network. Further, we examine the possibility of extinguishing the fire using a network of robots. Furthermore, we are evaluating the feasibility of robot aggregation by chaining between the robots for managing nominal and off-nominal operations.

F.7 CubeSat swarms in CisLunar space to identify, analyze, and characterize events of interest

Athip Thirupathi Raj, Jekan Thagavelautham
(Space and Terrestrial Robotic Exploration (SpaceTREx) Laboratory, University of Arizona)

One of the key goals of the Artemis program is to establish a sustainable presence on the Moon, including the development of lunar bases. These bases will be used for scientific research, resource exploration, and utilization and as a stepping stone for further solar system exploration. However, the development of lunar bases poses many challenges, including the harsh environment on the lunar surface, such as micrometeorite impacts, which are a safety hazard and threat to astronauts, especially with a lack of atmosphere on the moon to mitigate the effects. This calls for an Observation Post in CisLunar space to identify some events of interest, act as an early warning system, and characterize them.

We propose using a swarm of CubeSats as part of an Observation station in CisLunar Space outfitted with sensors of varying specifications. Using the “Smartphone camera” approach to sensors, where there are a variety of imaging sensors with varying focal lengths, field of views, and apertures, the probability of capturing an observation of an event of interest is significantly increased. “Scout” CubeSats equipped with lower-resolution sensors with a wider field of view provide information about the location of the event to an autonomous planner algorithm in real-time as they cover a wider area. The planner may redirect another CubeSat with a higher resolution sensor but a lower field of view to observe the event in greater detail. At the same time, the Scout is either retargeted to look for other events or to provide data from another view angle for sensor fusion. This scouting and retargeting approach is not possible with single large spacecraft, making CubeSat swarm the ideal candidate for satisfying such requirements.

This presentation discusses the elements of the mission design of a CisLunar Observation outpost using a swarm of CubeSats. First, we perform Physics-based 3D simulations to establish the need for such an outpost in CisLunar space and a genetic algorithm to optimize and find the minimum number of CubeSats and the combinations of onboard sensors required to observe all possible event occurrences. In addition, the onboard processing required to run the planner algorithm in real time is calculated. Finally, we propose real-world testing of our hypothesis using a swarm of drones in a controlled environment to observe randomly occurring simulated events of interest to determine the effectiveness of the autonomous planning algorithm.

F.8 Shape Memory Alloy Based Hard Docking Mechanisms for two-stage CubeSat Docking

Nicholas Gross, Athip Thirupathi Raj, Jekan Thagavelautham
(Space and Terrestrial Robotic Exploration (SpaceTREx) Laboratory, University of Arizona)

On-orbit docking methods already in use in larger spacecraft, such as the ISS, have a long history and a high TRL; however, on-orbit docking systems for small satellites have yet to be evaluated in a space environment. Currently, no docking mechanisms involve an airtight seal for transferring materials from one small spacecraft to another to permit on-orbit servicing. Instead, most proposed docking techniques for CubeSats use a single phase involving magnetic force (soft capture). Using magnets for docking is undesirable, as they cause Electromagnetic Interference (EMI) when one CubeSat’s electronics moves in the presence of a docking magnetic field. In addition, the electromagnets used for docking consume large amounts of power to maintain a docked configuration and require complex control algorithms to perform a successful dock. The electromagnetic force between the two CubeSats alone may not be enough to support an airtight seal for material transfer, hence calling for a mechanical latching system as a second stage in docking.

This paper discusses using geometric pairs of docking adapters with a second stage involving Shape Memory Alloy (SMA) spring-loaded latches. The geometric pair docking adapters are modified cones and probes which ensure proper mating irrespective of the x-y translational and z-rotational misalignment. They possess mechanical latches and slots on their faces, loaded by SMA springs. As the first docking stage is complete, the latches automatically lock onto the slots, creating the second stage hard dock without electrical power. The SMA spring contracts and releases the hard dock on command, and the two docking smallsats may use CubeSat propulsion to maneuver away from each other.

Based on the 3D simulation results and the analytical calculations, prototypes are developed for testing in simulated conditions in the laboratory. Ground-based systems such as 6-DOF robotic arms mimicking the ADC systems of the spacecraft and air tables to simulate the frictionless environment of space will be used to validate the designs. We aim to demonstrate a successful docking scenario between two CubeSats equipped with metal 3D-printed prototypes of our docking adapters. In addition, we aim to perform experiments to measure the precision, repeatability, and reliability of the SMA springs used in the adapters and arrive at requirements for space qualification of the mechanism. We further discuss the power consumption and optimization of the mechanism's mass, power, and volume.

Poster Session

P.1 Simulation Tool for Autonomous Multi-Spacecraft Mission Design around Small Bodies

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Over the past few years, the acceleration in technology development and maturation enables new capabilities and ambitions in terms of space mission design. In particular, the miniaturization of equipment for small-sat and CubeSat enhances the possibilities for multi-spacecraft mission architecture (e.g. Double Asteroid Redition Test (DART) and

Light Italian CubeSat for Imaging of Asteroids (LICIACube) mission; and Hera, Juventas, and Milani mission to Didymos-Dimorphos system). These new configurations however introduce new challenges during the preliminary mission design phase since the current tools are mostly tailored for single-spacecraft architectures and the number of feasible configurations grows exponentially for multi-spacecraft architectures. Thus, there is a need for a new generic and modular simulation tool for multi-spacecraft architectures, where each spacecraft is configured with different equipment, capabilities, and different mission objectives while being able to interact with other spacecraft in a common simulation environment.

Multi-Spacecraft Concept and Autonomy Tool (MuSCAT) aims to answer this need. It has been built for the Distributed Radar Observation of Interior Distributions (DROID) mission concept, which is a three-spacecraft architecture around the small-body Apophis. This case study illustrates the need for a such tool, having heterogeneous multiple spacecraft (e.g. attitude and navigation actuators, science instrument, guidance navigation and control instrument, power system, battery, solar panels, telecommunication), with different roles played during the mission and inter-spacecraft interactions (such as exchanging data or joint small-body science using multiple spacecraft’s instruments). MuSCAT’s objective is to iterate quickly from one mission design to another, allowing us to assess the design’s

success and performance in terms of science (small body coverage, data generated and sent to Earth) according to the technical design choices (e.g. actuators sizing and precision for orbit control and attitude pointing, data management and link budget between the spacecraft and for Direct-to-Earth communication, power management with equipment’s consumption and solar generation). MuSCAT also demonstrates the autonomy capabilities needed to achieve the mission goals. This paper describes the implementation and capabilities of the MuSCAT tool for one case study, the DROID mission.

P.2 Very Low Earth Orbit (VLEO) Satellite communication system design

Aman Chandra
(FreeFall)

Recent research into satellite communication services operating from VLEO show the potential for an improved link budget due to lower latency and shorter transmission distance to ground terminals. Such systems also reduce transmit power requirements and can enable higher frequency operations than Ka-band. Achieving a viable spacecraft design requires aerodynamic shaping and propulsion system considerations that dictate the useful lifetime of such satellites in orbit. In this work, we look at the feasibility of VLEO spacecraft as communication satellites. We present a system engineering approach towards the sizing and design of VLEO satellites focused on satellite communications. A rarefied gas dynamics approach is presented for aerodynamic shaping, considerations made on payload sizing, thermal design, power system design and communications system design and further described. Future work into understanding environmental impacts including effects of oxidative degradation, electrical charges and radiation effects are on-going. This work aims to look at the feasibility of a VLEO based satellite communications system.

P.3 Low Density Atmospheric Turbulence Measurement using Pitot Tubes

Adrien Bouskela, Chris Mason, Sergey Shkarayev
(University of Arizona)

Unsteadiness in atmospheric flows is of great importance to modeling accuracy and studies of airborne vehicle dynamics. These can include local variations in holographic winds, shear layers between high-speed regions, and perturbations due to thermal variations. In addition to weather modeling, all of these features are of interest for atmospheric energy extraction using fixed wing aircraft, meaning such data is of high engineering and scientific value. Yet, there is a gap in regular measurements on Earth and an absence of significant measurements on Mars. Although there are regular weather balloon launches on earth for high altitude measurements, wind is determined by the relative position of the balloon via a GPS sensor. On Mars, limit data is measured during spacecraft Entry Descent and Landing phases and at the landing site. For more detailed and global results simple distributed sensors are required.

The growing field of autonomous Unmanned Aerial Vehicles (UAVs) in the form of aircraft, rotorcrafts and controllable balloons offer an elegant solution to this problem. Any steady wind or turbulence present in the atmosphere is represented by their difference in ground relative and air relative velocities. With the ground velocity measurement being trivial, a sensor capable of high frequency measurements of the velocity relative to the atmosphere would complete the solution.

In the present work such a sensor is developed based on the proven pitot-static tube design. Multiple probes placed at known angles relative to the vehicle body provide the components required to determine both relative velocity magnitude and body relative angles. Analysis of flow components on the measuring ports of commercially available pitot probes is conducted. Experiments in a low-speed wind tunnel are performed, validating the system performance, analyzing its limitations, and conducting sensor calibration. Then, results from ongoing flight experiments using weather balloons will be presented. These Sensors have the capability of mounting on the previously presented Mars sailplane, completing its autonomous navigation system with accurate wind measurements of the environment while flying within it. Furthermore, dedicated missions are imagined, replicating daily NOAA launched on mars using the pitot-probe system and small spacecrafts. Proposing a method for comprehensive atmospheric measurements for remote planetary bodies.

P.4 Aerie: A Modern, Open Source Approach to Mission Planning and Scheduling

Eric Ferguson, Emine Basak Alper Ramaswamy, Christopher Camargo, Matthew Dailis
(Jet Propulsion Laboratory California Institute of Technology)

The use of mission planning and scheduling software appears throughout the design and operation of most, if not all, space missions. Usually, such software provides some modeling and simulation capability that allows planners to predict the integrated behavior of the spacecraft, ground, and environment and their effect on critical spacecraft resources including available energy, on-board data storage, and propellant consumption. Early in a project's lifecycle, many of these simulations can be run to quantify resource impacts to support trade studies, verify requirements, allocate resources, and assess the robustness of the design to perturbations. As the mission moves into operations, these simulations are then used to verify and validate a given plan prior to executing it on-board.

Aerie is a newly developed, open source planning and scheduling framework intended to support a wide range of mission classes from small sats to flagships. At its core, Aerie is a discrete event activity planning simulator that runs and orchestrates models in order to simultaneously simulate plan effects on flight, ground, and operations systems. Mission models are built and tested using a Java-based modeling framework, which can then be loaded into the Aerie system for planners to use to assess the viability of the plans they develop. Planners can either manually create plans using the Aerie user interface, or automatically build up a plan using Aerie's goal-based scheduling capability. Once a simulation has been performed on a plan, planners can check the validity of their plan through a javascript-based constraint checker. A command expansion framework within Aerie also provides the ability to directly generate spacecraft commands from activities within a plan.

Aerie is web-based, multi-tenant, and cloud-native, which enables distributed users to easily collaborate to build and assess plans. A powerful GraphQL API provides the capability for missions to easily interface Aerie with mission-specific applications or automate the generation of plans and sequences. Given Aerie is open source, the software is freely available for anyone to download, use, and modify. Aerie has created contribution guidelines and a governance model so that others can join the open source community and help shape the direction of future Aerie capabilities and development.

P.5 Modeling Small Satellites With Grapplers for Capturing Space Debris

Phillip Truong*, Leonard Vance**, Jekan Thagavelautham**
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Space debris is a growing problem in Earth Orbit. One of the main challenges is dealing with uncooperative space objects that may be large in size and irregular in shape. The intended motivation for a grappler satellite is to help with the de-orbiting of space debris in Low Earth Orbit. The grappler system is motivated by squid enveloping prey. Simulations are being performed to determine the efficacy of the overall approach. The central code involves modeling a satellite with 2 tether arms, creating a grappling satellite. Those 2 tether arms consist of 14 links each, allowing the links to act in series to envelop an object. An individual link only starts rotating when the previous link has already begun that process and has detected contact. The benefit of this slow, methodical process is that it allows the grappler to envelop an object in a low-force and low-energy manner. Initially, the grappler's grappling algorithm was successfully tested against only 1 object, a rectangular prism. However, for the grappler's purposes, just being able to grapple a rectangular object would not be enough. Thus we needed to create other differently shaped 3D objects to test the grappler against. First, a right triangular prism was created to get an understanding of the previous system that was in place. After doing this to achieve a better understanding of the previous coordinate system, it was revamped to a system more similar to the one in STL files. Following this system allows code to generate these triangles procedurally, compared to plotting all the coordinates manually. One of the main advantages of this system is it makes creating many objects or complex objects easier, as all that needs to be calculated are the object's origin points. This new system resulted in the creation of more shapes, those shapes are a pyramid, a cuboid, a sphere, and a cylinder. In the end, a Hubble telescope-shaped satellite was able to be created with multiple cylinders and cuboids. Testing the grappler against this Hubble object resulted in the grappler's arm slipping off and not enveloping the object. Although if the object was rotated 90 degrees, we believe that the grappler would have had an easier time grabbing onto the object. As for the aforementioned basic shapes, the grappler was successful in grappling the cuboids and cylinders, failing at grappling the pyramid, and the sphere shape was not able to be simulated. These tests indicate that for the typically shaped satellites, the grappler would be able to assist in deorbiting them. Future work in this research would involve the optimization of the grappler algorithm so that more accurate assumptions can be made.

P.6 Low Power LEDs for CubeSat Attitude estimation during proximity operations

Jaret Rickel, Athip Thirupathi Raj, Jekan Thangavelautham
(Space and Terrestrial Robotic Exploration (SpaceTREx) Laboratory, University of Arizona)

Attitude estimation of one spacecraft from another is a complex and challenging task that requires advanced technologies and techniques that involves determining the relative orientation and position of one spacecraft with respect to another. This task is essential for various applications, including space rendezvous and docking, formation flying, and satellite servicing. Optical, radar and radio-based techniques are existing technologies for relative attitude estimation. Optical methods rely on visual observations from cameras on one spacecraft to determine the relative position and orientation of the other spacecraft. This can be accomplished using computer vision algorithms to analyze images and extract critical features such as the position and orientation of the other spacecraft. However, Optical sensors can be affected by environmental factors such as sunlight and shadows. These factors can interfere with the accuracy of the measurements and lead to errors in attitude estimation. Furthermore, due to their small size, it is impossible to identify and track small satellites and CubeSats in space via ground-based optical observations.

We propose using a system of low-power LED lights on the outer surface of small spacecraft to aid with target identification and attitude estimation, in addition to Visible Light Communication (VLC) for proximity operations. We derive lighting requirements for spacecraft from the external lighting requirements for Aircraft imposed by the FAA and derive lighting requirements for small spacecraft and CubeSats. We perform target identification and attitude estimation experiments using low-cost commercial cameras such as the Arducam and the raspberry pi cam on CubeSat prototypes with LED pixels on their external surface mounted on 6 degree of freedom Robot Arms. We arrive at the minimum number of LED lights required to accurately estimate the relative orientation and rotation rates of the target CubeSats, as well as the onboard processing required to make the estimations. Finally, we propose the standardized “Lighting Module” addon for small spacecraft, which is less than 0.25U in volume and mass, attached to the outer panel of the satellite to aid in its identification and tracking both from ground and space-based observations. We analyze the implications of such an addon module regarding cost, power, mass, volume, and technology readiness for Low Earth Orbit and Deep Space smallsat missions.

P.7 Airborne Release and Recapture of UAV from Martian balloons

Christian LeClaire, Reed Spurling, Adrien Bouskela, Sergey Shkarayev, Jekan Thangavelautham
(Micro Air Vehicles Laboratory, University of Arizon)

Small fixed-wing aircraft hold great potential for analyzing new regions of Mars, allowing a dive into the topographical complexities of the planet. While rovers have completed much work on traversable terrains, there are rugged areas of the planet that are better suited to aircraft reconnaissance. Fixed-wing aircraft with remote sensors and in-situ instruments could collect significantly more data from a wider area at a lower cost. Inspiration can be taken from uncrewed aerial vehicles (UAVs) on Earth, a growing field where technology has been useful for military reconnaissance, emergency rescue operations, agriculture, and more. Furthermore, flight on Mars has been proven to be possible by the operationally responsive and scientifically valuable Ingenuity helicopter, a preview of the potential benefits of UAVs on Mars.

Small fixed-wing aircraft are proven to be able to fly with low energy consumption, as is apparent from extensive studies on the flight of gliders. The exploitation of wind allows for these aircraft to fly for considerable distances and durations while using minimal power. The same should be possible in other planets' atmospheres. While this capability presents great potential for further planetary exploration, it relies on specific wind conditions suitable for flight. Since such conditions do not always exist, we are researching the possibility of docking these vehicles when unsuitable weather is imminent and relaunching them when conditions are again suitable for flight. Assuming a stationary balloon-borne platform as a home base for the fixed wing aircraft, we will present two potential solutions to docking and relaunching: Perching, and the Brodie landing system.

The perching method uses aerodynamic forces as an aid for landing the small-winged aircraft at a specific point. Using an intense pitch-up maneuver and dynamic stall, the fixed wing aircraft can dock to its home base.

The Brodie landing system is a mechanical approach to the same challenge. In this system a hook on the aircraft is used to grab onto a moving carriage that slides along a cable suspended between two points.

These systems both have their benefits and drawbacks, and future research for them proves beneficial towards furthering the possibility of aerial, topographical studies conducted on Mars.

P.8 Science Yield improvemeNt via Onboard Prioritization and Summary of Information System (SYNOPSIS)

Mark Wronkiewicz, Gary Doran, Jakc Lightholder, Zaki Hasnain, Lukas Mandrake
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For many missions, the ability to collect data far outstrips the ability to transmit it to Earth. This is especially true for planetary science missions with targets beyond Mars. For these scientific communities, science autonomy algorithms are an area of interest because of their ability to summarize and prioritize scientific data onboard the spacecraft; they provide a means to maximize the science return of a mission in the face of severe data transmission constraints.

There are several examples of such autonomy systems at JPL including the Ocean Worlds Life Surveyor (OWLS) project for detecting life on Ocean Worlds, Responsive Onboard Science for Europa Clipper, and Content-based On-board Summarization to Monitor Infrequent Change (COSMIC) for Mars exploration. While future missions will benefit from the development of these algorithms, there is not yet a way to systematically deploy and operate multiple algorithms on one mission. This is a vital need as the volume and complexity of data acquired by spacecraft continues to increase.

SYNOPSIS aims to provide a reusable, easy-to-use framework to facilitate deployment of multiple onboard science instrument autonomy (OSIA) systems. It acts to integrate and prioritize data products even when data from multiple autonomously-powered instruments is present. Specifically, SYNOPSIS

1. Enables multi-instrument prioritization based on a tunable combination of utility and diversity. Utility prioritization favors data products with high intrinsic value (according to the science team) while diversity prioritization favors data products with “new” or “different” content.
2. Provides a rules-based mechanism to enforce inter-instrument relationships during data prioritization. For example, this is valuable when contextual and high-resolution instruments sometimes measure the same phenomenon.
3. Is integrated into the core Flight Software (cFS) and F-Prime flight software packages. This lowers the bar for future mission inclusion.

The SYNOPSIS code base is open source and we aim to provide a standard interface for other research groups to improve or reuse science autonomy algorithms or develop new ones to fit within the same framework. Please reach out if you wish to collaborate!

P.9 Simulation of LEO Lighting Conditions for Small Satellite testing

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Jekan Thangavelautham
(Space and Terrestrial Robotic Exploration (SpaceTREx) Laboratory, University of Arizona)

The possibility for on-orbit autonomous docking becomes more than just a desirable feature for CubeSats as the space industry continues to study and develop CubeSats as a financially viable alternative for satellite utilization. With the rapidly increasing interest in Optical Navigation, Space Situational Awareness, and Light-Based Communication, there is yet to be a known way to recreate the illumination conditions of space to test the different autonomous docking technologies theorized and prototyped. The development of simulated lighting conditions on Earth is crucial if the space industry is to enhance autonomous docking and other proximity operations, including formation flying and swarm control technologies in CubeSats. Some movie studios have built lighting studios with full-scale settings for movie sequences.

The creation of such a lighting environment, which we refer to as the Spacecraft Workings and On-orbit Robotics using Drones (SWORD) facility, is described in this study. The SWORD facility is a laboratory that simulates different light-emitting or light-reflecting celestial bodies that potentially impact the sensors of a CubeSat operating in low Earth orbit or deep space using various LED lights with variable intensities and hues. First, the LED lights have been set to mimic the hue and brightness of light emanating from the Earth, the Moon, and the Sun, and reflections from space debris, distant stars, and other similarly important illumination sources. Then, based on how a CubeSat is positioned with respect to the Earth, Sun, and Moon, calculations are made to determine how much illumination it receives under various lighting situations in LEO, such as sunshine and moonlight and total eclipse. These values are used to calculate the lux levels for the LEDs within SWORD. The brightness of the LEDs must be scaled down to match Commercial LED products for safety reasons while still producing correct results depending on the lighting needs. This facility will test light sensors to see whether they can be utilized for visual navigation or enable Visible Light Communication (VLC) between two or more CubeSats. SWORD will be the first to offer a realistic, easily accessible space illumination environment. The facility has far-reaching ramifications and will enable onsite testing of communication between two or more CubeSats, giving information on the hardware and software requirements of the CubeSats while in LEO and deep space.

P.10 Subterranean Exploration Using a Train of Autonomous Vehicles

Nicholas Blanchard, Adrien Bouskela, Jekan Thanga, Sergey Shkarayev
(University of Arizona)

The work presents a conceptual design of a system of drones for the exploration of caves and lava tubes. Caves and lava tubes provide a unique environment for preserving microbial life. Orbiters have discovered dark pits on the surface of Mars that resemble caves or lava tubes. By analogy with Earth, caves on Mars may contain signatures of past microbial life and become valuable resources of lava-flow thermodynamics and hydrodynamics gravity. The objective of the present project is the development of the autonomous vehicles system for the exploration of caves and lava tubes featuring environments analogous to expected on other planets, e.g., Mars.

Previous publications have outlined localization and mapping methods to undertake complex and GPS-denied navigation inside terrestrial cave environments. LiDAR and onboard cameras are often used in an optical flow arrangement for local position estimation. Similarly, this conceptual system employs a simultaneous localization and mapping (SLAM) algorithm, time of flight (ToF) sensor, stereo image sensors, and tracking image sensors to facilitate navigation in indoor environments.

However, the conceptual system expands upon previous work by proposing a swarm of drones and beacons communicating through a ground station. Multiple drones explore in a train configuration, deploying WiFi beacons along the way to provide continuous communication between the drones and ground station, even around sharp corners. The detection of the cave entrance and finding the pathway in an unknown and inaccessible environment is based on an artificial intelligence algorithm integrated into specialized flight controller software.

The experimental program aiming to validate the developed system is underway. GPS-denied navigation and visual-inertial odometry (VIO) based localization are being tested in laboratory conditions while the machine learning based feature recognition is being tested in outdoor caves. Recent development and testing centers on a custom ground control algorithm that harnesses MAVLink communication to provide fully autonomous control for the drones in the GPS-denied environment.

The preliminary results of this study demonstrate the feasibility of autonomous drone exploration in GPS-denied environments and provide a running start for the leader-follower arrangement proposed to control multiple drones in a train configuration.

P.11 Evaluation of Artificial Neural Tissues for Small Multirobot Networks in Handling Emergencies Onboard Next-Generation Space Stations

Jekan Thangavelautham, Siva Muniyasamy, Athip Thirupathi Raj, Min Seok Kang
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Rapid advances in mobile computation, miniature low-cost sensors, actuators, and power systems are making a transformative impact on next-generation terrestrial buildings and facilities. Imagine every brick in a home can think, sense, plan, and predict, actively looking out for dangers, including toxins, fire, and smoke, facilitating efficient heating and cooling, and providing timely and precise info about components about to fail. Such capabilities applied to the world of aerospace could offload the day-to-day operational challenges on next-generation space stations like the Lunar Gateway or a lunar surface base. Conditions on the lunar surface and lunar orbit are challenging, as it is the dangers of solar flares, micrometeorites, intense temperature swings, and lunar surface dust. We propose a system of system solution called SMART that would utilize a decentralized pocket cloud capability that computationally powers a network of smart sensors and small robots to perform dull, dirty, and dangerous tasks. The proposed robots would perform routine patrols, cleaning, repairs, and asset management tasks. The computational backbone can allow for utilizing complex physical models to forecast and make optimal decisions with incomplete and even imprecise sensor data.

The system's computational backbone is hyper-redundant and is being designed for handling all types of dull routine tasks, in addition to emergencies where human occupants may become trapped and be mentally impeded/shocked due to fast-changing outcomes. In this presentation, we explore the potential applications, including the use of advanced machine learning and AI techniques called Artificial Neural Tissue to make efficient, even optimal decisions. In this presentation, we show how a network of robots learns to fight fire efficiently and, through this process, learn to evolve novel cooperative behaviors. This approach will remain as a comparison to human-programmed approaches to tackle the same challenges. With the machine learning approach, we hope to learn creative solutions to solve multi-robot decision-making tasks. Through these experiments, we hope to determine the overall feasibility of using a team of agile small fire and emergency handling robots for use on space stations and lunar habitats. The applications for this technology could also have implications for a human Mars mission and human habitats in Cislunar space.

P.12 Energy Cost of Outposts on Asteroids

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Whether it be towards making humanity a multi-planetary species or towards reducing resource scarcity on Earth, space mining will be a critical undertaking of the near future. Space mining is, however, a still-emerging field that is exceedingly difficult to achieve with our existing space infrastructure. Therefore, it has become important to pick mining targets carefully. Currently, the prevailing hypothesis is that the moon is the best fit to be humanity's "first step" due to its proximity, but that is only one facet of mission difficulty. Asteroids provide a fundamentally different but equally lucrative mining environment–their higher concentrations of resources of interest mean less mining equipment needs to be hauled and maintained to achieve the same output and their lower gravity reduces .V costs. The objective of this study is to quantitatively summarize and compare the difficulty of establishing mining operations on various asteroid targets. This difficulty measure is represented by the sum of the electrical and kinetic energy costs accrued by asteroid mining infrastructure over their operational lifecycle. These energy costs will be presented as equations parameterized in terms of variables representing the mining conditions and the equipment properties. The mining operations in question are envisioned as a surface outpost exporting refined materials while supplied by mobile robotic miners. The output of various outposts (measured in mass) is held constant so energy costs better correlate with difficulty. Each possible outpost picks mining equipment out of a standardized set relevant to its asteroid's characteristics: distance from Earth, hydration, metal concentration, surface cohesion, and site. Certain mining subsystems do not consume a significant amount of solar energy, but their mass is tabulated to derive the kinetic energy necessary to establish an outpost from .V numbers. Outpost energy consumption can be divided into five broad categories: importation of infrastructure, excavation, refining, robotics, and exportation. Generally, near-Earth asteroids outperformed main-belt asteroids for ease of importation and exportation, as outposts on the former set of asteroids could make use of solar sails. .V accessibility from Earth is also lower for NEAs. Hydrated targets proved necessary to maintain an interplanetary supply chain based on rockets due to the ISRU production of H2 and O2. The only other asteroid characteristic that impacted this energy category was size, as landers would be necessary to ferry products from the surface to an orbital depot. Mining energy costs favored low cohesion or differentiated asteroids, as scooping materials requires less force than drilling them. Monolithic metallic NEAs are an exception, supporting a mining architecture centered on orbital mirrors, which do not consume electrical energy. Refining favors hydrated targets over anhydrous metallic ones. Not only is water easier to thermally separate from regolith, but refining systems that operate solely on electrical energy are rare. Material separation is further complicated by the milligravity asteroidal environment. For surface locomotion, the viability of tumbling robots and rovers would depend entirely on their engineering statistics. Rovers are restricted to the largest asteroids but have a higher TRL. Overall, hydrated NEAs rise to the top of energy accessibility among the asteroids, and likely outperform the moon as well. These asteroids, however, are rare. When these asteroids are not an option, hydrated main-belt asteroids outperform anhydrous NEAs, although economic demands may necessitate that both types of asteroids be mined. Smaller asteroids with less cohesion do generally well in terms of energy cost, although there are other difficulties associated with these targets not covered by this study, such as the technological readiness of anchoring mechanisms. Going forward, this energy study can be further refined by examining more outpost subsystems. Studies examining difficulties that cannot be encapsulated by an energy number can be used to corroborate these results and help determine the best "first step" mining target for humanity.

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