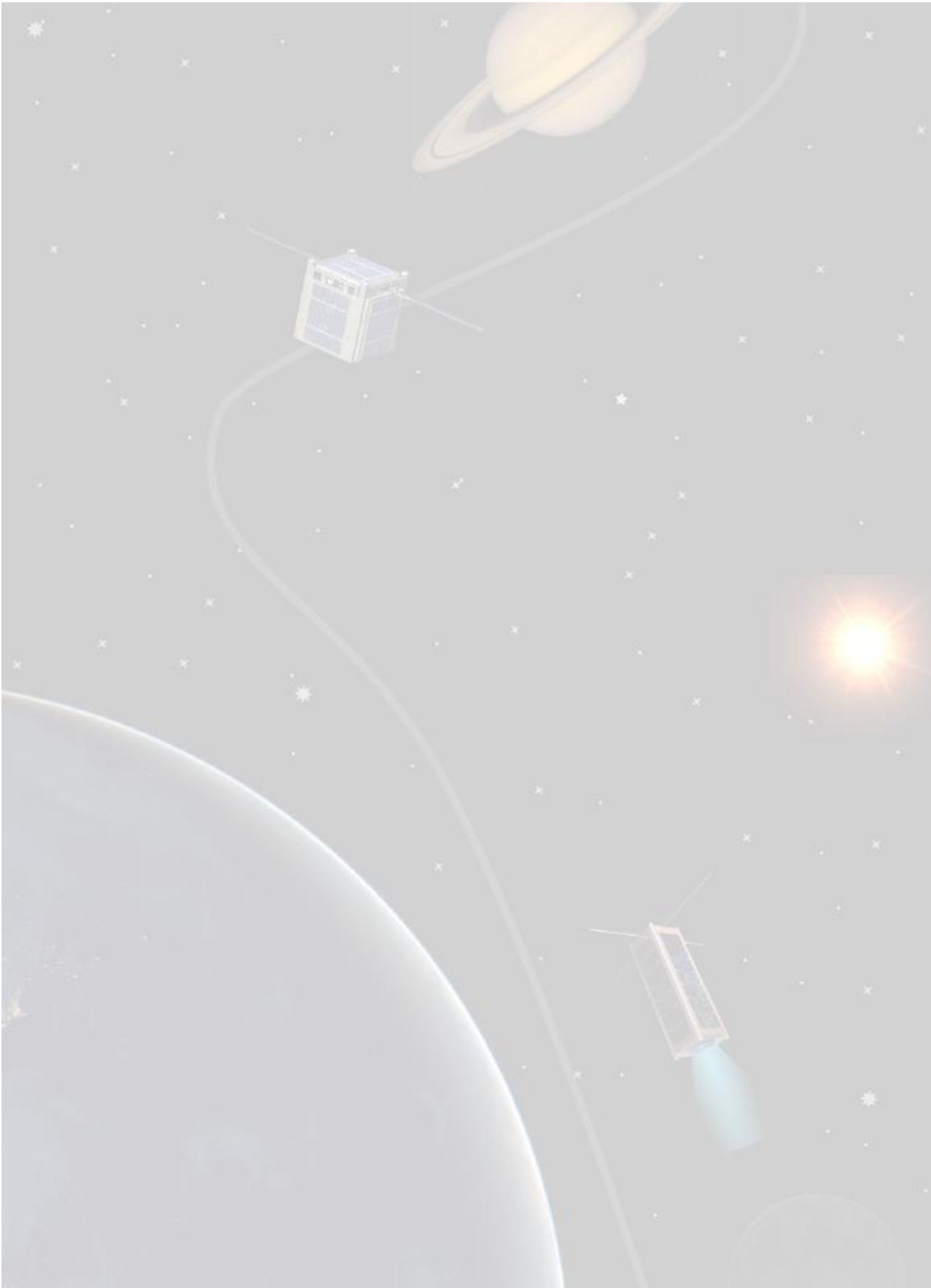
April 30th -May 2nd, 2024
University of Arizona



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Conference Agenda

Tuesday, April 30th, 2024

Time (PDT)	Event
7:45-8:45	Registration and breakfast
8:45-9:00	**Opening Remarks (A. Babuscia)**
9:00-10:00	**Keynote Speaker: A. Polit (University of Arizona)** **Rendezvous with a small body: OSIRIS-REx at asteroid Bennu and preparations for OSIRIS-APEX at Asteroid Apophis** *Moderator: J. Thangavelautham*
10:00-10:20	Coffee break
10:20-12:05	**Session A: Lessons learned from interplanetary small satellite missions ready to launch or currently operating** *Session Chairs: A. Babuscia and J. Thangavelautham*
	A.1 SunRISE - Opening a New Window on the Sun *(J. Lux)* A.2 CAPSTONE: A Highly Successful Mission Demonstrating Autonomous Navigation and Operations Technologies in the Cislunar Domain *(T. Gardner)* A.3 Precision Surface Mapping of Apophis during 2029 Flyby using a Cubesat Swarm Deployed from Geostationary Orbit. *(L. Vance)* A.4 BioSentinel: Update on extended mission operations *(A. Dono)* A.5 Mars ESCAPADE small interplanetary satellite *(C. Mandy)* A.6 ESCAPADE: Lessons Learn for low cost Mars missions *(R. Lillis)* A.7 CatSat: A University of Arizona CubeSat for Technology Demonstration and Scientific Research *(W. Rahmer)*
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15:50-17:35	**Session C: Ground support and operations for interplanetary small satellite missions** *Session Chairs: K. Angkasa and K. Buckmaster*
	C.1 In Favor of Supervisory Control Operations for Small Satellites using NASA's Deep Space Network *(M. Starr)* C.2 Future Deep Space Mission Communications Trends with Potential Implications for Smallsats *(D. Abraham)* C.3 Cost Effective Strategies and Tools for Interplanetary Mission Operations *(A. Tripathi)* C.4 On the Efficacy of Student Operations for Interplanetary Spacecraft: Benefits and Challenges *(A. Yeung)* C.5 Multiple Uplinks Per Antenna (MUPA): Where Are We Now? *(D. Abraham)* C.6 Spacecraft-Initiated Operations with the Deep Space Network *(J. Lazio)* *C.7* SunRISE Mission Operation System Overview *(J. Lux)*
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18:05-18:15	**Day 1 Closing Remarks: A. Babuscia**
18:15-20:00	Dinner

Wednesday, May 1st, 2024

Time (PDT)	**Event**
7:45-8:45	Registration and breakfast
8:45-9:00	**Opening Remarks (A. Babuscia)**
9:00-10:00	**Keynote Speaker: D. Scheeres (University of Colorado)** **What's up with Janus? The past, present and future pathway of a NASA SIMPLEx mission** *Moderator: M. Saing*
10:00-10:20	Coffee break
10:20-12:05	**Session D: Telecom, C&DH, software, network technologies for small satellite missions** *Session Chairs: C. Lau and C. Lee*
	D.1 Enhancements and Redesign of Iris Radio *(T. Russell)* D.2 The JPL Snapdragon Co-Processor *(Z. Tawfic)* D.3 Overview of CADRE Flight Software Developed using the F Prime Flight Software Product Line *(A. Rizvi)* D.4 Sensor Network using smart sandbag for autonomous lunar construction *(M. Villasana)* D.5 Distributed architectures for cislunar communication and navigation services *(A. Chandra)* D.6 Machine learning algorithms for lunar base operations using a network of small robots *(S. Muniyasami)*

	D.7 Localization and Pose Estimation of Planetary Surface Assets Using Active Lighting Cues *(M. Kang)*
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Thursday, May 2nd, 2023

Time (PDT)	Event
7:45-8:45	Registration and breakfast
8:45-9:00	**Opening Remarks (A. Babuscia)**
9:00-10:00	**Keynote Speaker: J. Whitten (Smithsonian Institution)** **Unveiling Venus: Past and Future Exploration of our Sister Planet** *Moderator: A. Babuscia*
10:00-10:20	Coffee break
10:20-11:50	**Session F: Upcoming and innovative mission concepts for small satellite missions** *Session Chairs: A. Babuscia and K. Angkasa*
	F.1 Smallsat-aided Mission for the 2029 Apophis Rendezvous: ATENA *(G. Saita)* F.2 Terrarium Controller to Imitate Lunar Conditions for Live Organisms *(A. Antonic)* F.3 Ciclunar spacecraft assembly for near earth surveying *(A. Bouskela)* F.4 Space Song Foundation: The Tree of Life *(J. Christensen)*

	F.6 SUMS: Supporting a Uranus flagship Mission with SmallSats *(D. Barnes)* F.7 Global Mapping of Lunar Surface Water and Hydroxyl in Context *(T. Livengood)*
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13:30-15:30	**Session G: Technologies for interplanetary small satellite missions** *Session Chairs: C. Lee, P. Clark, and K. Buckmaster*
	G.1 Origami Solar Arrays for Small Space Systems *(N. Van der Leeuw)* G.2 Inflatable Shelter for Extraterrestrial Protection *(A. Torres)* *G.3* High Frontier: A Low Thrust and Autonomous Navigation Mission for Near-Earth Asteroid Excavation *(D. Velez)* G.4 A Novel Excavator for an Asteroid Mining Context *(K. Hansen)* G.5 Experimental Investigation of Rotor Model with Blowing Jets *(E. Greenfield)* G.6 Enabling Deep Space Exploration Using Inspectors Accompanying Small Spacecraft System of Systems Architecture *(K. Chauhan)* G.7 ACORN: the Advanced Compact Orbiting Radar for luNar sounding *(S. Nerozzi)* *G.8* CLEW (Compact Lunar Explorer for Water): State of the Art IR Spectrometer for a Lunar Cubesat Orbiter *(P.E. Clark)*
15:30-16:00	**Session G Q&A Panel: C. Lee, P. Clark and K. Buckmaster**
16:00-16:20	Coffee Break
16:20-17:35	**Session H: Wings, sailplanes, and balloons technologies for interplanetary small satellite missions** *Session Chairs: C. Lau and G. Ogden*
	H.1 Conceptual design of unpowered glider for soaring flights in the Martian atmosphere *(A. Bouskela)* H.2 Exploring the Martian canyons by means of atmospheric energy harvesting *(A. Bouskela)* H.3 Improving Wind Model Profile for "1-cos" Discrete Gust *(K. Nietzel)* H.4 Train of Autonomous Aerial Vehicles for Subterranean Exploration with SLAM Capabilities *(N. Blanchard)* H.5 Balloon-Based High-Altitude Air Turbulence Measurement *(R. Spurling)*
17:35-17:55	**Session H Q&A Panel: C. Lau and G. Ogden**
17:55-18:00	**Conference Closing Remarks: A. Babuscia**

Welcome

Welcome to the 2024 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, and the SpaceTreX Laboratory at University of Arizona. 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 at University of Arizona.

— *The Organizing Committee*

Registration Hours and Contact Information

The registration desk will open everyday of the conference from 7:45 am to 3pm. 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 has been the 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.

Dr. Greg Ogden is a Research Professor in the Department of Chemical & Environmental Engineering at the University of Arizona. He manages the Department's Unit Operations Laboratory, maintains bench and pilot-scale equipment and works to upgrade & enhance the undergraduate laboratory facilities. Dr. Ogden's Research interests span the gamut from green propulsion to optical sensing microalgae to In-Situ Resource Utilization (ISRU) of regolith from celestial bodies to workforce development related to Solar Technology.
Dr. Ogden has over 30 years' experience in process design, facility management, environmental remediation and novel technology development. He is registered as a Professional Engineer (Chemical) in Arizona.

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 Wi-fi Information

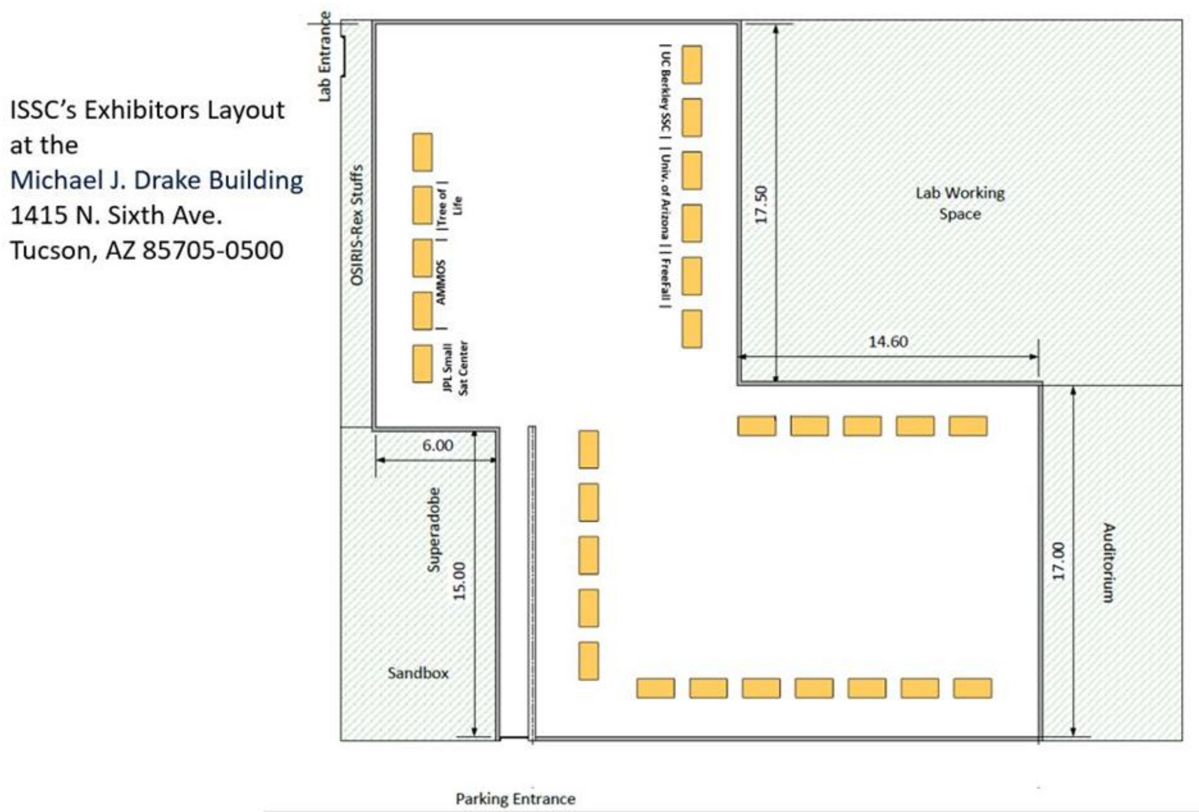
The conference will be mainly held at the Drake Building at the University of Arizona. Parking is provided at no cost and it is available in the back of the building, as shown in the map below:

Tours and dinner on day 2 will be in the main part of the university campus. Bus shuttles will be available to bring conference attendees from the Drake building to the tour location and back to the Drake at the end of the event, if people prefer to leave the vehicles parked at Drake. Alternatively, parking is available on Cherry St. Garage (cost $9), location is indicated in the map below.

There will be a specific Wi-fi 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. All meals (except dinner on Day 2) will be provided in the same exhibitor area.

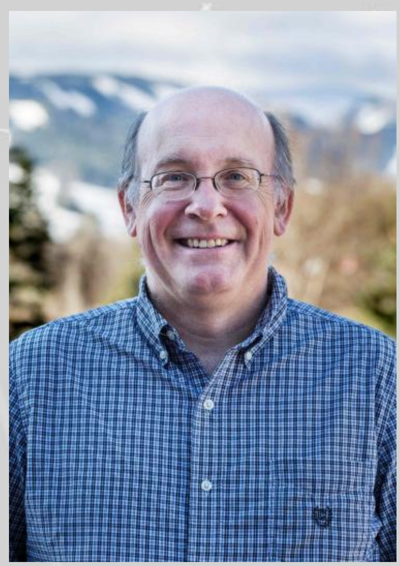


Keynote Speaker Biographies

Anjani Polit

Anjani Polit is the Mission Implementation Systems Engineer for the OSIRIS-REx asteroid sample return mission and the Mission Implementation and Control Officer for the OSIRIS-APEX mission to explore asteroid Apophis. During OSIRIS-REx proximity operations around asteroid Bennu, she led the OSIRIS-REx Science Planning Team and was the Vice-Chair of the Sample Site Selection Board. For OSIRIS-APEX, Anjani manages spacecraft observation planning and oversees daily operations at the mission's Science Processing and Operations Center. She also provides management oversight for science team finances, scheduling, and resource allocation. Anjani has participated in proposal and operations development for a number of missions and previously served as the Program Manager for the University of Arizona Earth Dynamics Observatory. Before OSIRIS-REx, Anjani was the Uplink Operations Lead for the HiRISE camera on the Mars Reconnaissance Orbiter.

Dan Scheeres



Daniel Scheeres is a University of Colorado Distinguished Professor and the A. Richard Seebass Chair in Aerospace Engineering Sciences at the University of Colorado Boulder. Following a five year tenure at the Jet Propulsion Lab's Navigation Systems Section and professorships at Iowa State University and the University of Michigan, Scheeres joined the Department of Aerospace Engineering Sciences in 2008. He has since become a vital member of the Colorado Center for Astrodynamics Research community, heading the Celestial and Spaceflight Mechanics Laboratory. Scheeres has graduated 37 PhD students in his career who now hold positions in academia, U.S. and international research labs, and industry, 18 of these while at CU.

Scheeres' research spans the topics of astrodynamics and spacecraft navigation to planetary science and celestial mechanics and has published extensively in these fields. One primary focus of Scheeres' research is studying the mechanics of small bodies (such as moons and asteroids) with applications to planetary and asteroid missions. A separate focus of Scheeres' research is in the field of Space Situational Awareness, where his lab studies the dynamics and estimation of orbital debris and active satellites. Most recently, Scheeres is serving as the Radio Science Lead and Co-Investigator for NASA's OSIRIS REx Asteroid Sample Return Mission.

Scheeres is a Fellow in the American Institute of Aeronautics and Astronautics, a Fellow in the American Astronautical Society, and president of the Celestial Mechanics Institute. He is a member of the American Astronomical Society's Divisions on Planetary Science and Dynamical Astronomy, the International Astronomical Union and the International Astronautical Federation. He was awarded the Dirk Brouwer Award from the American Astronautical Society in 2013 and gave the John Breakwell Lecture at the 2011 International Astronautical Congress. Asteroid 8887 is named "Scheeres" in recognition of his contributions to the scientific understanding of the dynamical environment about asteroids. He was elected to the National Academy of Engineering in 2017.

Dr. Jennifer Whitten

Jennifer Whitten holds a B.S. in Geology from the College of William and Mary in 2009 and a M.Sc. and Ph.D. in Geology from Brown University in 2011 and 2014. She completed a postdoc at the Smithsonian National Air and Space Museum before becoming an assistant professor at Tulane University. She has returned to the Air and Space Museum as a Research Geologist. Her research focuses on processes that generate and modify planetary crusts by combining a variety of space-based and ground-based data types. Her current research focuses on classifying ancient terrains on Venus and tracking the production and distribution of sediment on the surface of Venus. She has participated in several mission and instrument science teams, including the Moon Mineralogy Mapper instrument on Chandryaan-1, the Mars Reconnaissance Orbiter SHARAD instrument, and the MESSENGER team. She is Associate Deputy Principal Investigator for VERITAS.

Conference Abstracts

K.1 Rendezvous with a small body: OSIRIS-REx at asteroid Bennu and preparations for OSIRIS-APEX at Asteroid Apophis

Anjani Polit
(University of Arizona)

The OSIRIS-REx spacecraft rendezvoused with asteroid (101955) Bennu in 2018 and executed a comprehensive campaign to characterize the asteroid, culminating in sample collection in 2020 and delivery of the sample to Earth in 2023. OSIRIS-REx has been successful despite the challenges and complexity of the mission. While the OSIRIS-REx sample analysis team continues to systematically study the pristine asteroid sample, the renamed OSIRIS-APEX spacecraft is on a new trajectory to rendezvous with asteroid (99942) Apophis in 2029. The spacecraft will approach Apophis shortly after the asteroid makes a historic close approach to Earth which will change the asteroid's orbit and subject it to tidal forces. This talk will provide a summary of the OSIRIS-REx mission, discuss lessons learned, and provide an overview of plans for the OSIRIS-APEX mission.

K.2 What's up with Janus? The past, present and future pathway of a NASA SIMPLEx mission

Dan Scheeres
(University of Colorado)

Janus was selected in 2019 as a SIMPLEx mission to be co-manifested with the NASA Discovery mission Psyche, scheduled to be launched in August 2022. Janus was designed to send two spacecraft to fly by Near Earth Objects of interest. Each of the Janus spacecraft can be targeted to fly by a separate asteroid. The original targeted asteroid systems were the binary asteroids (175706) 1996 FG3 and (35107) 1991 VH, both of which have been observed repeatedly with photometry, spectrometry and radar and have intriguing scientific questions that the mission was to address.

The 2022 launch delay of the Psyche mission led to the two Janus spacecraft (S/C) to be de-manifested from the Psyche launch, as the new launch provided no viable scientific mission opportunities for Janus. The S/C are now in storage at a NASA center, and are available for future use.

In this talk I will provide a detailed description of these innovative small satellites and their pathway to the current situation. Potential future uses for these S/C for interplanetary science and exploration missions will also be discussed, including their possible use for a future Apophis flyby mission in advance of its Earth close approach.

K.3 Unveiling Venus: Past and Future Exploration of our Sister Planet

Jennifer Whitten
(Smithsonian Institution)

Venus and Earth share many similarities – these planets are nearly the same size and average composition. Venus, however, is currently far less hospitable. Venus is in a runaway greenhouse, giving a surface temperature of 460°C. The atmosphere is a crushing 92 atm. Venus lacks Earth-like plate tectonics, yet the surface is very young, with many potential indications of geologic activity. Despite being next door, many unanswered questions remain about our sister planet.

NASA selected the VERITAS mission to go to Venus around 2030. The overarching goal of the mission is to understand how Venus and Earth evolved down two very different paths – one supremely 'habitable' and the other – not so much. The mission will investigate: (1) the role of water – did the plateaus form when there was liquid water near the surface? Is water still coming out of volcanos? (2) active geologic processes– what kinds of volcanos and tectonic features? Is the wind moving sediment across the surface, and (3) Since Venus doesn't have Earth-like plate tectonics, what is the overall tectonic system that keeps Venus' surface so young? VERTIAS will reveal an entirely new Venus. The mission will provide global datasets with vastly better resolution than Magellan: topography (20x), imaging (10x), gravity (~8x), surface NIR spectroscopy (>20x SNR). Additionally, VERITAS will collect Repeat Pass Interferometry data to detect cm scale surface deformation. Venus is an incredibly rich scientific target, with many compelling science questions accessible to SmallSats. Science topics range from atmospheric escape, atmospheric composition, monitoring seismic activity transmitted into the atmosphere to searching for crustal magnetization.

A.1 SunRISE - Opening a New Window on the Sun

James Lux, T. Joseph W. Lazio, Cate Henegan
(Jet Propulsion Laboratory, California Institute of Technology)

SunRISE will open a new window on space observation of low radio frequency emissions. SunRISE is an observatory of six 6U space vehicles flying in a loose formation about 10 km across in a GEO+300 km orbit. The six space vehicles form the sensing part of an interferometer to image Type II and III radio emissions from the Sun between 100 kHz and 23 MHz. These frequencies are blocked by Earth's ionosphere, so observations must be made in space. SunRISE is unusual in that the "instrument" is composed of both the flight system and the ground processing, which forms the ultimate science products. JPL will operate the space vehicles. University of Michigan (UM) will process the science data.

In operations, the six space vehicles record the DecaHectometric (DH – 100 kHz to 23 MHz) signals and Global Positioning System (GPS) observables continuously. Once a week, the space vehicles are contacted via the Deep Space Network (DSN) to downlink the data and to uplink schedules for the coming weeks, including any trajectory correction maneuvers needed to maintain the relative positions of the space vehicles.

This presentation summarizes the implementation of SunRISE, which is currently in storage awaiting launch (as a rideshare provided by US Space Force), commissioning, and a year of operations, most likely in late 2024 or 2025. The space vehicles are composed of a spacecraft, designed and built by Space Dynamics Laboratory (SDL), and a JPL-designed and built payload. SDL conducted the integration and test of the individual space vehicles, while JPL conducted a unique Interferometer Level Performance Test (ILPT), which was an end to end test of the entire system. The ILPT was a collaborative effort among JPL, SDL, and UM, in which simulated GNSS and solar signals were fed to all the space vehicles at once; the ground systems communicated via a simulated Deep Space Network link, simulating flight operations; a week's worth of data retrieved by the ground systems team was then passed to the UM science processing pipeline.

The paper describes challenges encountered during the formulation and implementation phases, how the SunRISE team overcame them, and a summary of the lessons learned. Considering SunRISE as a trailblazer for multi-spacecraft observatories at the Moon and beyond, there are additional lessons for communications and navigation. For example, deep space constellations won't have helpful aid of GPS.

A.2 CAPSTONE: A Highly Successful Mission Demonstrating Autonomous Navigation and Operations Technologies in the Cislunar Domain

Thomas Gardner, Brad Cheetham, Jeffrey Parker, Alec Forsman, Nathan Re, Anthony Zara
(Advanced Space, LLC)

Tethers Unlimited, and NASA have partnered to develop, launch, and operate the Cislunar Autonomous Positioning System Technology Operations and Navigation Experiment (CAPSTONE) mission, which is serving as a dedicated precursor for Near Rectilinear Halo Orbit (NHRO) operations in cislunar space. Over the past ~28 months, this low-cost, high-value mission has demonstrated an efficient, low-energy orbital transfer to the Moon, a successful insertion into the NRHO, and ~23 months of successful operations in the NRHO while demonstrating key technologies in support of the NASA Artemis lunar exploration program. These technologies include 1) The CAPS autonomous navigation technology using both two-way ranging with the Lunar Reconnaissance Orbiter (LRO) and one-way uplink ranging with the Deep Space Network (DSN) 2) Demonstration of our Neural Net for Electric Propulsion (NNEP) technology for autonomous maneuver planning and execution and 3) Demonstration of our Sigma Zero technology for spacecraft anomaly detection and classification.

The Cislunar Autonomous Positioning System (CAPS) is a peer-to-peer real-time system for autonomously estimating absolute position and velocity for spacecraft operating in the cislunar environment. The CAPSTONE spacecraft has executed multiple successful ranging passes with LRO and validated onboard the CAPS algorithm performance. The software has also been used to estimate absolute navigation states using one-way uplink ranging signals to the SDL Iris radio combined with a high-precision Chip Scale Atomic Clock (CSAC) and algorithms provided by JPL.

NNEP is a maneuver design algorithm that uses neural networks as function approximators to map the current state of a spacecraft to a corresponding maneuver. The onboard test on CASPTONE demonstrated a neural network trained to design the orbital maintenance maneuvers (OMMs) for CAPSTONE.

Sigma Zero performs anomaly detection and classification via a neural network model. CAPSTONE has executed the onboard test of this software, downlinked the neural network output as telemetry packets, and verified that the result matches what was expected. The onboard testing used data generated on the ground to correctly identify a maneuver mismodel in Kalman filter post-fit residuals. Subsequent testing was executed to identify and autonomously classify eight additional types of anomalies.

This presentation and paper include an overview of this NASA technology focused mission, lessons learned from the 2+ years of successful operations, a summary of the challenges encountered, and an overview of the results from the CAPS, NNEP, and Sigma Zero autonomous navigation technology demonstrations.

A.3 Precision Surface Mapping of Apophis during 2029 Flyby using a Cubesat Swarm Deployed from Geostationary Orbit.

Leonard Vance, Harish Vernekar, Jekan Thangavelautham
(SpaceTREx Laboratory, University of Arizona)

In May of 2029, the OSIRIS-ApEx (Renamed from OSIRIS-Rex) mission will perform a rendezvous with the Near-Earth Asteroid Apophis, at which time it will enter orbit and conduct research using the sensor suite which has proven itself during its multi-year mission to Bennu. Approximately one month before this rendezvous, Apophis will experience a near-Earth encounter, approaching to within 31,600 km of the Earth Surface, allowing a rare opportunity to collect scientific imagery without executing an interplanetary mission.

By executing a flyby of a cubesat swarm, we propose to collect images from multiple locations during flyby, allowing generation of a precise shape model at the time Apophis is approaching Earth. This can then be compared to measurements by OSIRIS-ApEx in months following rendezvous to ascertain any surface changes resulting from Earth tidal forces, a key element in understanding internal cohesion.

An overview of the proposed mission is presented, giving delta-V usages and timelines starting as a secondary target from geostationary orbit. Basic photometrics are executed to establish baseline camera performance, and dynamical calculations are done to establish the slew performance of standard cubesat configurations, leading to a baseline number of spacecraft and requirements for angular acceleration, field of view and flyby distance.

A.4 BioSentinel: Update on extended mission operations

Matthew Napoli, Andres Dono
(NASA Ames Research Center)

BioSentinel has achieved unprecedented performance of an SLS secondary payload due to preparation, planning, and a robust design. Following the conclusion of the primary science mission in April 2023, the Linear Energy Transfer (LET) Spectrometer has continued to collect solar and galactic radiation data from its unique location in heliocentric orbit. The free space dataset offered by the BioSentinel LET is a valuable source of data for both model validation and future mission planning. As the spacecraft travels farther from Earth it is poised to provide longitudinally distributed measurements of solar particle events during solar maximum.

Flight heritage has now been gained on many of the novel spacecraft components. The spacecraft bus continues to operate within the design envelope. The 3D-printed cold gas propulsion system provides momentum unloading from the reaction wheels. The power system has maintained power positive levels during flight. The IRIS radio communicates on a weekly basis with the Deep Space Network. The extended mission operations are allowing the team to characterize the performance of the spacecraft components over longer durations of operations.

NASA Ames led development of the BioSentinel spacecraft and mission operations. The novel subsystems and COTS components that comprise the BioSentinel bus can serve as a template for future deep space missions. With over a year of continuous operations, the data will inform the next generation of interplanetary Smallsat missions.

A.5 Mars ESCAPADE small interplanetary satellite

Christophe Mandy
(RocketLab)

Rocket Lab has been building two spacecraft for UC Berkeley’s Space Sciences Laboratory for the NASA Escape and Plasma Acceleration and Dynamics Explorers (ESCAPADE) mission to Mars. The mission will place two spacecraft in Mars orbit to understand the structure, composition, variability, and dynamics of Mars' unique hybrid magnetosphere, demonstrating Decadal-class small spacecraft capabilities for Mars. The mission is currently undergoing its final phases and slated to launch in September 2024. This paper will discuss the ESCAPADE spacecraft CONOPS and the flexible development cycle which allowed the design to proceed well past CDR while staying agnostic to launch vehicle and ultimate trajectory. We will focus in particular on trajectory margining, design flexibility and production processes to allow for rapid late-stage design or requirement changes.

A.6 ESCAPADE: Lessons Learn for low cost Mars missions

Robert Lillis*, David Curtis*, Ellen Taylor*, Shannon Curry**, Shaosui Xu*, Jeff Parker***
*(*UC Berkley Space Sciences Laboratory, **Laboratory for Atmospherics and Space Physics, University of Colorado, ***Advanced Space, LLC)*

ESCAPADE is a twin-spacecraft Mars mission concept that will revolutionize our understanding of how space weather conditions drive magnetic structure and flows of energy and momentum throughout Mars' unique hybrid magnetosphere.

ESCAPADE will measure magnetic field strength and topology, ion plasma distributions as well as suprathermal electron flows and thermal electron and ion densities, from precessing elliptical 150 x ~8500 km orbits. ESCAPADE are small spacecraft (<200 kg dry mass) following ballistic Hohmann transfers to Mars. Our strategically-designed 1-year, 2-part scientific campaign of temporally and spatially-separated multipoint measurements in different regions of Mars' diverse plasma environment, will allow us to untangle spatial from temporal variability and unravel the cause-and-effect of solar wind control of ion and sputtering escape for the first time. ESCAPADE is due to launch on Blue Origin's New Glenn launch vehicle in September 2024. This presentation will focus on expected science topics to be investigated and on lessons learned by NASA and the ESCAPADE team that may be applied to future low-cost planetary and heliospheric science missions.

A.7 CatSat: A University of Arizona CubeSat for Technology Demonstration and Scientific Research

Walter Rahmer, Shahe Henley
(University of Arizona)

CatSat is a technology demonstration and scientific research satellite designed and built primarily by students at the University of Arizona in partnership with Tucson companies. As more spacecraft enter low-Earth orbit each year, there is an increasing need to improve the downlink speed of small satellites and understand more about the Earth’s atmosphere. CatSat is a 6U CubeSat designed to test a new inflatable antenna technology and conduct ionospheric research with a WSPR (weak signal propagation reporter) antenna. The satellite will demonstrate the use of this novel inflatable antenna design to allow for future highspeed communication, as current small spacecraft are limited in data transmission capabilities by stringent size constraints. CatSat also contains a high frequency (HF) radio/antenna system designed to probe the Earth's ionosphere during twilight. With the successful completion of spacecraft vibration testing, CatSat is fully qualified for launch in 2024. Student experience has been key to the mission since its beginning, with numerous students from different departments and class levels participating. Throughout the duration of the mission, students will be involved in commanding the spacecraft and processing scientific data. Additionally, future derivatives of CatSat for more ambitious missions are in formulation, using the inflatable antenna for both science and telecommunications.

B.1 Solar Sail Propulsion For Alternate Redirection Project

Alec Maloney, Samantha Stevens, Shae Henley, Jackson Barger, Christian LeClaire, Sergey Shkarayev

(University of Arizona)

The Solar-SPAR project focuses on the design of a CubeSat equipped with a solar sail to harness naturally occurring solar flux to use in a novel alternate propulsion method to maneuver a secondary payload into a new orbit. Centripetal acceleration is created by maximizing the amount of solar flux on the solar sail by tilting the sail canopy in 90-degree increments. This flux imparts a small force, causing the CubeSat assembly to rotate around its center of gravity. A secondary payload kept inside the spacecraft will be released when the CubeSat assembly is rotating, allowing the assembly to impart an increase in velocity to the secondary payload upon its release, delivering it into a new orbit. Such dynamic maneuvering has the capability to be used in many applications, such as for deorbiting debris and potentially changing satellite orbits around the Earth, with the benefit of providing a low cost, low pollution method to assist with the implementation of future advancements in technology. This project includes parametric studies of solar sail motion, as well as conceptual and detailed designs of the CubeSat systems and deployment mechanisms, and an analog prototype designed and built for application on Earth.

B.2 Thin-Film Kirigami Actuators for Solar Sail Attitude Control

Hanseong Jo, Christopher Le, Howard Trinh, Isaac Shih
(Department of Physics and Astronomy, University of California, Los Angeles)

Solar sails are of great interest for high delta-V missions and ability to support non-Keplerian orbits. Future developments necessitate light-weight and very large area systems. Attitude control of such systems presents a big challenge. Here, we discuss integrating thin-film kirigami actuators within the solar sail membrane to manipulate local radiation pressure. Specifically, we explore electrothermal actuation mechanism, assessing the performance and system requirements through a combination of experimental and simulation methods. We show actuation of a cantilever of >20° with a temperature increase of <10°C and demonstrate 2D-bulging and kirigami actuators. Integrating this technology into solar sails has the potential to significantly enhance solar sailing capabilities and potentially enable a range of novel missions.

B.3 Lunar Flashlight: Propulsion System Challenges and Insights from a Lunar CubeSat Mission

Celeste Smith
(Jet Propulsion Laboratory, California Institute of Technology)

Lunar Flashlight, a NASA Lunar CubeSat mission, was a technology demonstration meant to enter Lunar orbit and use the onboard infrared spectrometer to map the distribution of ice deposits on the Lunar south pole. The mission was a demonstration of multiple novel technologies including the propulsion system utilized to achieve Lunar orbit. The propulsion system itself incorporated several new technologies such as the use of ASCENT monopropellant and an additively manufactured titanium distribution manifold. The propulsion unit, developed by Georgia Tech in conjunction with NASA's Marshall Space Flight Center, offered both performance and safety advantages over traditional hydrazine-based propulsion systems. Utilizing additive manufacturing for the distribution manifold allowed the novel method of building fuel lines directly into the propulsion system structure.

During the mission's first in-flight reaction wheel desaturation maneuver it became evident that the propulsions system's thrusters were underperforming. This jeopardized its chances of reaching lunar orbit. Creative methods of performing the necessary Trajectory Correction Maneuvers were devised, including rotating the spacecraft around the axis of a single thruster while firing and reversing the pump to disrupt blockages in fuel lines. Ultimately, thruster performance became too low and Lunar Flashlight left the Earth-Moon system, settling in to a heliocentric orbit.

An anomaly analysis was performed which ruled out failure modes like electronics issues or thruster damage due to vibration from launch. The accepted conclusion is that debris became lodged between each thruster valve and thruster feed tube or in the valve after the seat. The debris could have been particles from the 3D-printed manifold becoming dislodged during testing and launch load vibrations or debris that was not properly cleared during the cleaning process. The effect of the debris could have been mitigated by including more filters along the propellent flow path and debris may have been avoided by using a surface finishing process on internal passages. Following the production of the 3D-printed part, it could undergo a CT scan to verify cleanliness, and a hot fire test could be conducted to verify system performance.

While Lunar Flashlight ultimately settled into a heliocentric orbit, the mission provided valuable insights into the challenges of utilizing novel and additively manufactured propulsion systems in space exploration. Lessons learned from this experience contribute to the ongoing refinement of propulsion technologies for future lunar missions and beyond.

B.4 Delta-V Distributions for Mission Requirements Towards an Interstellar Object

Adam Nekolny, Leonard Dean Vance, Jekan Thangavelautham
(University of Arizona, SpaceTREx Laboratory)

Interstellar objects fascinated the scientific community with the detection of 1I/’Oumuamua in 2017 and later Borisov in 2019. Their observation has determined that their structure and appearance can vary, ranging from an interstellar comet to an interstellar asteroid, as highlighted by Oumuamua. While no missions have been conducted to rendezvous with an interstellar object due to challenges such as short detection time and lack of standby launch opportunities, their prospect in scientific explorations is significant as they could provide material insight into other solar systems. As such, it is important to determine the distribution of delta-v's required to reach interstellar objects within a specific flight time. Therefore, this presentation aims at showcasing the distribution of necessary minimum delta-v’s across an extensive range of time of flights. This is done by running a Monte Carlo simulation on thousands of interstellar objects' trajectories throughout a detectible range, which, based on the detection range of Borisov, has been determined at 3 Astronomical Units from Earth. Within this detection range, the simulation goes through each interstellar object trajectory at variable times of flights; from the range of flight times the one required, the minimum delta-v is recorded, after which the distribution of these velocities is plotted and analyzed. The analysis focuses on determining the range of delta-v’s for which a small spacecraft mission would be feasible. For the small spacecraft mission, different sizes are considered to determine which configuration would most likely be successful in reaching the interstellar object, with the mission's primary focus being flyby and secondary objective of an impact mission. Throughout each of the mission types, the scientific objectives on material analysis or surface mapping are considered. Furthermore, the distribution of different percentiles of the overall simulated pool is plotted to determine the number of reachable interstellar objects through conventional propulsion methods usable on small spacecraft. Overall, the simulation aims to determine how many objects are expected to be reachable and if a small spacecraft would be a viable approach for one of these low-cost missions.

B.6 Exquadrum's FORGE Development & Test Site: Current & Future Propulsion Testing Capabilities

Eric Schmidt, David Morrison

(Exquadrum Inc.)

For the last six years, Exquadrum has been building a test and development capability at its FORGE site for the verification, validation, and development of liquid engines and solid rocket motors. The site spans the ability to test in-space propulsion, including a fully permitted and licensed capability to store, handle, and test hypergolic propellants; component level and prototype subsystem test and development, including energetics; to full rocket propulsion systems and stages up to 50,000 pounds of thrust. The FORGE site sits on over 33 acres and provides a complete complement of engineering and technician support. This presentation also will describe Exquadrum's future expansion plans as it works to build a world-class test and development site for future propulsion programs.

B.7 Overview of High Efficiency, Compact Rotating Detonation Rocket Engines

James Villarreal
(Noble-works)

Rotating Detonation Rocket Engines (RDREs), a type of pressure gain device, represent a revolutionary advancement in propulsion technology, offering significant improvements in efficiency and thrust-to-weight ratio compared to conventional combustion engines. This presentation provides a comprehensive overview of RDREs, exploring their fundamental principles, operating mechanisms, and current development status. Furthermore, it investigates the potential utility of RDREs in future space missions, assessing their capabilities in enhancing spacecraft propulsion systems for various applications such as launch vehicles, satellite maneuvering, deep space exploration, and interplanetary travel. Finally, we present recent test successes and lessons learned at Nobel Works Corp, an Arizona company focused on pressure gain devices. This presentation sheds light on the promising prospects of RDEs in revolutionizing space propulsion, addressing challenges, and unlocking new frontiers in space exploration.

C.1 In Favor of Supervisory Control Operations for Small Satellites using NASA's Deep Space Network

Mason Starr
(Georgia Institute of Technology)

Despite significant advances in spacecraft autonomy in recent years, the fact remains: developing sophisticated autonomy is expensive. Cost and complexity can be reduced by allocating decision making capability to adaptable human operators or ground software rather than investing in brittle spacecraft automation. The extended two-way contacts provided by NASA's Deep Space Network (DSN) enable a supervisory control mode of operations, which allows missions to execute complex activities that are beyond the capabilities of their spacecraft's autonomy. Using supervisory control, or "joysticking", introduces risks, which will be discussed along with their mitigations. These attributes make supervisory control an appealing, but largely unexplored, mode of operations for beyond-Earth small satellite missions due to their typically constrained budget, use of DSN, and relaxed risk posture. Lessons learned from the Lunar Flashlight mission, which made extensive use of supervisory control, will be condensed to inform the development of autonomy and operational processes for future missions.

C.2 Future Deep Space Mission Communications Trends with Potential Implications for Smallsats

Douglas S. Abraham, Jay Wyatt
(Jet Propulsion Laboratory, California Institute of Technology)

Each year, in support of NASA’s Space Communications and Navigation (SCaN) Office, JPL’s Interplanetary Network Directorate (IND) performs a variety of analyses focused on future deep space mission communications trends and their loading and capability implications for NASA’s Deep Space Network (DSN). Among other things, these analyses suggest that there will be periods of significantly increased loading on the DSN during which elevated mission contention for DSN antenna support can be expected. Key drivers for these potential contention periods include: (1) the advent of high-priority/high-visibility human lunar exploration missions, (2) a significant increase in the sheer number of missions – both robotic and human, and (3) a gradual increase in the number of spacecraft per mission, on average.

To the extent that these factors conspire to reduce available tracking time, there may be increasing pressure to limit deep space antenna support to the larger, more expensive deep space missions. Ironically, the lower-cost deep space smallsats frequently need large ground antennas, since they have the least amount of onboard power for their transmitters and least available “real estate” for their antennas.

Fortunately, NASA has been supporting a number of emerging developments in the deep space communications realm that may help future smallsat missions deal with this dilemna. These developments include: (1) the emergence of university and commercial satellite communications providers with 20-meter-plus antennas, (2) DSN introduction of a downlink-only Opportunistic Multiple Spacecraft Per Antenna (OMSPA) service, (3) technology development efforts focused on making the DSN’s traditional MSPA service essentially two-way via a new Multiple Uplinks Per Antenna (MUPA) technology, (4) technology development efforts involving spacecraft autonomy, beacon tones, and chip-scale atomic clocks that could allow spacecraft to only “phone home” when necessary, and (5) flight project adoption of Delay Tolerant Networking (DTN) for more reliable and efficient communications across multiple space and ground assets. Together, these emerging developments should eventually generate and/or free up additional communications capacity for the growing deep space smallsat “fleet.”

C.3 Cost Effective Strategies and Tools for Interplanetary Mission Operations

Abhishek Tripathi, Dan Cosgrove, Bryce Roberts
(UC Berkley Space Sciences Lab)

The UC Berkeley Space Sciences Lab has worked with a relatively small budget and a team of less than 20 people to operate spacecraft in Lunar and Heliocentric orbits, and soon in Mars Orbit (NASA ESCAPADE mission). We have a highly automated Mission Operations Center with tools, both homegrown and purchased, that has helped enable complex operations in a cost effective manner. Here we highlight the lessons learned from our last decade of operations, and present strategies for interplanetary mission operations in a budget constrained future.

C.4 On the Efficacy of Student Operations for Interplanetary Spacecraft: Benefits and Challenges

Alan Yeung*, Mollie Johnson**, Graham Jordan*, Mason Starr*, Glenn Lightsey*
*(*Georgia Institute of Technology, **Massachusetts Institute of Technology)*

Lunar Flashlight (LF) is a 6U CubeSat developed by NASA’s Jet Propulsion Laboratory (JPL) with the original purpose of demonstrating a novel green propulsion system and mapping surface water ice concentrations at the Lunar South Pole. In a novel approach to interplanetary mission operations, Lunar Flashlight was fully operated by students, both undergraduate and graduate, at the Georgia Institute of Technology (GT). This presentation analyzes the steps and effectiveness of having students operate a low-class mission such as LF. Before launch, student operators were trained by JPL experts, contributed to integration and testing (I&T) activities, and developed critical procedures and ground data system (GDS) software to be used in flight. After launch, the team worked with the Deep Space Network (DSN) daily and satisfied all mission success criteria while ensuring the health and safety of the spacecraft. Although the primary mission was cut short due to a malfunctioning propulsion system, students in conjunction with JPL executed multiple incidental activity campaigns including a propulsion diagnostic, imaging, and laser firing campaign. While the official JPL end of mission was declared in May 2023, GT operations continued until December 2023. During the extended mission, ownership of the spacecraft was completely given to GT. The fully student-driven extended mission led to the success of an optical navigation campaign. Several challenges emerged due to the uniqueness of having students operate an interplanetary spacecraft, such as dealing with a high turnover rate, academic scheduling conflicts, and the knowledge gap between undergraduates and graduates. However, several benefits emerged as well: reduced operations overhead, stronger institutional partnerships, and a streamlined transition from school to industry. The valuable learning opportunities from Lunar Flashlight operations are applicable to future parties who may wish to pursue a similar operations structure in the future.

C.5 Multiple Uplinks Per Antenna (MUPA): Where Are We Now?

Douglas S. Abraham, Shantanu Malhotra, Leila Meshkat, David D. Morabito, James A. O'Dea, Emily R. Pascua, Marc Sanchez-Net, Dong K. Shin, Luke C. Stewart, Zaid J. Towfic

(Jet Propulsion Laboratory, California Institute of Technology)

JPL is currently developing an antenna beam-sharing technology for uplink communications known as Multiple Uplinks Per Antenna (MUPA). Traditionally, antenna beam-sharing has primarily involved multiple in-beam spacecraft simultaneously downlinking through the same antenna via a technique known as Multiple Spacecraft Per Antenna (MSPA). But, uplink on this shared antenna has been relegated to a serial swapping of the uplink from one spacecraft to the next – with a 10-30 minute reconfiguration period between each spacecraft swap. MUPA aims to enable the spacecraft simultaneously downlinking during an MSPA session to also be able to near-simultaneously uplink at the same time (as well as perform simultaneous 2-way Doppler and ranging) – thereby allowing more efficient use of the DSN's antennas.

In-beam opportunities usually exist for spacecraft at Mars, Venus, and more distant locations. Even at the Moon, the DSN's very narrow 34m antenna beam covers an area that easily encompasses most postulated human lunar surface missions. Properly designed constellations of spacecraft can also share the same beam. And, secondary payloads launching off of a primary mission's upper stage will typically be within beam together for many hours until executing maneuvers to insert into their individual trajectories. The more smallsats can take advantage of these beam-sharing opportunities, the more likely it is that they will be able to obtain time on deep space antennas that are otherwise dominated by communications with larger, more expensive deep space missions.

To make uplink beam-sharing opportunities available in the first place, our efforts to date have focused on: (1) developing and ground testing the Forward Communications Link Transmission Unit (FCLTU) Multiplexer needed to combine the command streams intended for the different participating spacecraft, (2) developing the Iris radio capabilities needed to work with a multiplexed command stream, and (3) performing the system engineering needed to understand what it might take to incorporate a MUPA capability into the Deep Space Network (DSN) – from both a flight demonstration perspective and an implementation perspective.

Future MUPA efforts will focus on moving from the current ground testing efforts to in-flight demonstrations. Initial in-flight demonstrations will entail proving out the FCLTU Multiplexer, as well as process changes within the DSN needed to accommodate MUPA session scheduling, uplink configuration, and two-way radiometric product generation for navigation. Subsequent in-flight demonstrations of MUPA-qualified flight radios (e.g., Iris) will also need to occur to prove out the flight-side capabilities needed to operate with a shared, single-frequency uplink.

C.6 Spacecraft-Initiated Operations with the Deep Space Network

Marc Sanchez Net*, Jay E. Wyatt*, T. Joseph W. Lazio*, Rebecca Castano*, Benjamin K. Malphrus**, Chloe Hart**)

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

The Deep Space Network (DSN) has traditionally supported missions using a predefined schedule that is negotiated up to six months in advance. Each project requests DSN time based on operational plans and activity forecasts, and a well-defined scheduling and deconfliction process is then followed to generate a viable DSN seven-day schedule. During any day of operations, the DSN follows this seven-day schedule as a master plan indicating which spacecraft would be enabled by each antenna, at what time, and the services and equipment that will be used for mission support.

Motivated by a combination of two factors: an increase in popularity of CubeSats and SmallSats, both in near-Earth, cis-lunar, and deep space, and the desire to reduce mission operations costs, the DSN has been exploring new technologies and operational concepts to increase the number of supportable missions with the available ground infrastructure. We describe one such effort, which focuses on prototyping the necessary capabilities to enable spacecraft-initiated operations via a DSN demand access service. In spacecraft-initiated operations, time on DSN antennas is not provided based on the seven-day schedule; rather, it is requested by the space-craft based on decisions made on board by its autonomy engine. The request is placed by having the spacecraft transmit DSN beacon tones to a smaller antenna (e.g., 18-21 meters in diameter), known as the queuing antenna, which provides frequent but short contacts with all spacecraft utilizing the demand access service. Once received, the request is automatically forwarded to both mission operations and to the DSN scheduling services. If needed, time on larger DSN 34 m or 70 m antennas is then allocated in near-real time, with a lead-time of 30 minutes to 2 hours.

We describe the results of the prototyping efforts conducted at JPL to deploy and operationalize the DSN demand access service, including the results of a flight demonstration conducted in 2023 with the BioSentinel spacecraft. To flight-validate the request mechanism, we describe the first attempt to send DSN beacon tones from a JPL Iris radio on board a CubeSat to the 21 m antenna at Morehead State University (affiliated with the DSN, also known as DSS-17). We also demonstrate the ability to automatically forward the received requests from the station to the DSN network operations center and the DSN Scheduling Service (SSS), both located at JPL.

C.7 SunRISE Mission Operation System Overview

Shannon Berger, Jim Lux
(Jet Propulsion Laboratory, California Institute of Technology)

SunRISE is a NASA Heliophysics mission that uses a loose constellation of six toaster-sized SmallSats operating as a radio interferometer about 10 km across to study coronal mass ejections. This mission will be operated utilizing AMMOS Instrument Toolkit (AIT) software on a custom development branch for ground software, with Open Source Mission Control Software (OpenMCT) for operator's data visualization. There is automation to assist with data storage and notifications of data availability to stakeholder teams. SunRISE uses the Deep Space Network (DSN) to communicate with the space vehicles and is operated from a Mission Support Area at JPL. The DSN will communicate with three space vehicles during a 5-hour pass using its Multi Spacecraft Per Aperture (MSPA) capability. This requires two passes per week to communicate with the entire constellation of six space vehicles.

The mission has unique challenges stemming from cybersecurity for the use of MSPA. The space vehicles only communicate with the ground and will have no ability to communicate with each other. This puts the burden on the Mission Design and Navigation team to ensure adequate spacing of the spacecrafts. Unlike LEO spacecraft which have frequent (but short) communications, SunRISE's operations need to be planned well in advance, given the weekly cadence of operations. There is some opportunity for real-time interaction in response to health checks performed at the beginning of the pass. Due to SunRISE's infrequent communication and potential for missed DSN passes, the Space Vehicles have onboard scheduling that covers several weeks. This scheduling is a collaborative effort between the Mission Operations Center (MOC) at JPL and Science Operations Center (SOC) at the University of Michigan.

This presentation provides some of the unique aspects for a multi-space vehicle mission, with shared communications once a week, operating near Geostationary Orbit (GEO). This operational cadence is different than the typical deep space mission, and different from the usual daily cadence for Low-Earth Orbit (LEO) small satellites.

D.1 Enhancements and Redesign of Iris Radio

Tom Russell, Dana Sorensen, Jon Hunt, Tim Neilsen
(Space Dynamics Laboratory)

Iris Radio has proven to be a robust and flexible flight telecom platform for small, deep-space missions, providing successful communications to all 12 spacecraft that have flown with an Iris through the end of 2023. The original hardware design (v2.1) allowed for X-band transmit and receive only and limited the opportunity for more complex mission topologies.

To serve the needs of the deep-space community, the Iris Radio team has significantly improved the capability and usability of the Iris Radio (now v3.0), allowing full duplex, multi-band, and multi-channel configurations and reduced size, weight, and power (SWaP). The updated design includes a significant increase in mission memory enabling additional applications such as delay tolerant networking (DTN) and store-and-forward operation. The firmware design has also been updated based on lessons learned from past missions to improve usability and fault handling. The updated design remains flexible for additional mission-specific requirements and features.

In this presentation, we discuss the expanded capabilities of Iris v3.0.

D.2 The JPL Snapdragon Co-Processor

Zaid Towfic, Dennis Ogbe, Sara Janamian, Andre Jongeling, Douglas Sheldon, Joseph Sauvageau

(Jet Propulsion Laboratory, California Institute of Technology)

The Jet Propulsion Laboratory has developed a high-performance co-processor board based on the Qualcomm Snapdragon System-on-Chip (SoC). This board is referred to as the JPL Snapdragon Co-Processor (SCP). The heart of the SCP is the Snapdragon 8155 SoC, which boasts an octa-core CPU complex comprising of quad ARM Cortex A-76 cores and quad ARM Cortex A-55 cores. All CPU cores can support 128-bit NEON vector instructions and the CPU cluster boasts > 100,000 DMIPS compute capability. In addition to the CPU, the SoC also hosts an Adreno 640 graphic processing unit (GPU). The GPU's dual execution units with 384 shaders/unit can deliver nearly 900 GFLOPs of performance at FP32. Finally, the SoC also hosts a digital signal processor (DSP) that can deliver 7 TOPs. The DSP is highly optimized for quantized neural network inference, FFT computation, among other fixed-point operations.

The co-processor board can operate independently, with 128Gbit of onboard memory and 1024Gbit Flash storage, and 2Mbit FRAM. Additionally, the co-processor board provides a variety of interfaces independently of its main connector to a carrier board. These external interfaces include dual USB 3.1 Gen 2 ports (10Gbps each), 4x 4-lane MIPI Camera Serial Interface Connector (40Gbps total/D-PHY v1.2 or 68 Gbps total C-PHY v1.0), as well as a boot select jumper.

The SCP can be hosted by a variety of carrier cards but has been extensively tested with the JPL Swift carrier card. The internal interfaces to the carrier card from the co-processor board include 2 lane PCIe (16Gbps), 1 lane PCIe (8Gbps), 1x GigE RGMII support, 2x UART, 1x JTAG, 14xGPIO, and 5x SPI/I2C/UART. The Swift carrier card itself hosts a Kintex KU060 Rad Tolerant FPGA, flight interfaces such as Spacewire or RS-422, SerDes interfaces, and its own memory. Additionally, the Kintex FPGA is monitored by a housekeeper RTAX or ProASIC FPGA.

Both boards (the Swift Carrier Card and the SCP) have passed JPL's TRL-6 assessment process, which assessed both boards for temperature, mechanical (vibration and shock), and radiation effects. Several missions are assessing the use of both boards, including radar and gravitational science missions.

D.3 Overview of CADRE Flight Software Developed using the F Prime Flight Software Product Line

Aadil Rizvi
(Jet Propulsion Laboratory, California Institute of Technology)

NASA's CADRE (Cooperative Autonomous Distributed Robotic Exploration) project is scheduled to launch on Intuitive Machine 3 (IM-3) mission and explore the Lunar surface as an autonomous team. CADRE is a technology demonstration consisting of multiple small mobile robots and a base station that can map their surroundings and compute trajectories enabling the rovers to drive in a formation and explore a region as a team. Also, certain health metrics are collected and shared across each participating agent in the team which can be used to elect a leader responsible for computing trajectories, drive times, regions and sleep times for each agent to explore in a coordinated fashion.

CADRE's flight software is based on the open-source F Prime Flight Software Product Line developed by JPL. The modularity and reusability of the framework provided by F Prime enables inheritance of various flight software capabilities from the framework and other projects, such as Mars Helicopter, which are also based on the F Prime Flight Software Product Line. The Qualcomm Snapdragon based VOXL platform, developed by Modal AI, is used on each CADRE agent as the hardware platform for executing the software deployment. F Prime, along with its use on Mars Helicopter's VOXL platform, provides a suite of flight-proven capabilities enabling development and test of a highly complex software system on a challenging timeline. Using F Prime allows software development to stay autonomy focused, thus highlighting the quality and reliability of F Prime. This presentation provides an overview of CADRE flight software, facilitated by use of the F Prime Flight Software Product Line, and its integration and test on multiple hardware venues to verify CADRE's cooperative and distributed autonomous functionalities.

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D.4 Sensor Network using smart sandbag for autonomous lunar construction

Michael Villasana. Camden Nelson, Siva Muniyasami, Jekan Thangavelautham
(Space and Terrestrial Robotic Exploration (SpaceTREx) Laboratory, University of Arizona)

NASA's Artemis program is a series of missions aimed at returning humans to the Moon, aiming to land and ultimately create a permanent presence of humans on the Moon. These missions will also support the development of a sustainable lunar economy in the coming decades as a stepping stone for future missions to Mars. One of the formidable challenges encountered in this endeavor is the development of lunar infrastructures. The harsh environment makes it difficult for astronauts to work on lunar constructions. Thus, the autonomous system plays a major role in lunar construction, eventually constructing self-sustainable lunar bases.

As there is no infrastructure to support autonomous lunar construction, it faces specific obstacles, chiefly in robotics assistance: communication, navigation, localization, computing resources for pose estimation. Moreover, the deployment of large, intricate robots via large interplanetary spacecraft poses major technical challenges. Therefore, an interconnected system of compact robots employing sophisticated multi-robot coordination tactics emerges as a promising solution for lunar construction endeavors. Alongside a sensor network, one can create a processing network that may act similarly as a super computer for heavier tasking. The critical element in multi-robot coordination for lunar surface construction is a sensor network to solve the Position, Navigation, and Timing (PNT) and to facilitate effective assembly strategies. In our previous work, we proposed SMART architecture consists of autonomous systems, including a network of autonomous robots for construction, distributed computing, and smart sensors units for situational awareness handling lunar construction. To address these challenges, in this work, we propose smart sandbags as multi-functional building blocks equipped with smart sensors to estimate location and orientation for assisting a network of small robots during lunar structure assembly. These networks will be employed using the interplanetary CubeSat class micro-processors for lunar missions. These smart sandbags form a sensor/processing network to assist the robot in communication, navigation, localization and mapping the lunar surface.

A prototype model for a sensor network consisting of smart sandbags designed to assist in lunar construction alongside autonomous robots is currently developed. The smart sandbag network will be further demonstrated through physical software and hardware implementations. Future references will explore the advancement of these models into fully functional prototypes, adapting to real environmental conditions.

D.5 Distributed architectures for cislunar communication and navigation services

Aman Chandra
(FreeFall Aerospace, Inc)

A renewed interest in human exploration of the Moon, also seen as a suitable training premise to prepare for future Mars missions, has led to multiple lunar surface and orbital missions in advanced stages of development and operation. A large amount of government and commercial investment in these missions has led to the creation of a cislunar economy that is set to grow at a steady pace over the next decade. A robust communications infrastructure is fundamental to any credible human presence on the moon and beyond. A fundamental challenge with orbital antenna systems in cislunar space is high gain beam steering at low power. FreeFall Aerospace has developed spherical reflector antennas that are lightweight, low power and offer a multi-band capability. As such these antennas have been designed to offer compact stowage in small satellite platforms. A spherical geometry allows mechanical beam steering with a stationary reflector. Such systems have been developed for lunar orbit and lunar surface operations. In this work, we present network architectures to optimize DTE access and expanded coverage to the polar regions of the Moon. The architectures are based on distributed surface and orbital antenna systems developed at S, X and Ka band. The presented architectures focus on scalability and multi-functionality to meet communications and navigation needs.

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D.6 Machine learning algorithms for lunar base operations using a network of small robots

Siva Muniyasami, Jekan Thangavelautham
(SpaceTRex Laboratory, University of Arizona)

NASA's Artemis program aims to establish a sustainable human presence on the Moon by establishing a lunar base. However, the harsh lunar environment poses significant challenges for astronauts, which necessitate using autonomous robots to construct and operate the lunar base. Building on our previous work, we propose a team of small robots and sensor networks to manage daily operations and emergencies within a manned lunar base, enhanced by AI/ML capabilities for task scheduling, planning, and resource allocation. These robots will operate within a modular, pressurized chamber of the lunar base via ceiling-mounted tracks. A decentralized computer architecture using radiation-resistant computing tiles and smart sensor units will monitor the environment and enable dynamic resource allocation. This architecture offers enhanced resilience and adaptability in the unpredictable lunar environment. Drawing inspiration from warehouse automation but recognizing the unique challenges of the lunar base, we developed software to conduct experiments and optimize the base's layout and robot operations. We will use advanced Guidance, Navigation, and Control (GNC) algorithms to optimize robot coordination and task execution. We will implement conventional Decision Tree (DT) and Finite State Machine (FSM) control algorithms. We will compare these algorithms with various parameters. Evaluation will focus on factors like cycle time, energy consumption, points of failure, robot count, and throughput in inventory management and emergency scenarios. Robot configuration and response simulations will help determine the optimal number of robots for peak efficiency. This will provide insights into optimizing lunar base layout, resource allocation, and robot configurations for various lunar base operations.

D.7 Localization and Pose Estimation of Planetary Surface Assets Using Active Lighting Cues

Min Seok Kang, Athip Thirupathi Raj, Jekan Thangavelautham
(University of Arizona)

Recently, there is renewed interest in lunar exploration and development, both by governments and private entities. Future plans for such initiatives include the construction of semi-permanent structures on the lunar surface, and in-situ resource utilization (ISRU). These tasks are expected to be done by teams of small robots, and the coordination of multiple surface assets requires localization. However, the Deep Space Network is limited in the number of users it can support, and orbital assets may take time to reach full coverage in the area of interest. To solve this problem, we built upon our previous work in CubeSat navigation. Previously, we have used active lighting cues, inspired by navigation lights on aircraft, to estimate the attitude of CubeSats for proximity operations. Now, we apply this method for robots on planetary surfaces. Similar to our previous work, we propose using lighting cues for the localization and the pose estimation of surface assets. Our method uses lights mounted atop towers on the lunar surface. Such towers have been proposed as a multifunctional platform for providing support services to lunar surface assets, such as lighting, communications, and the monitoring of activity. In this system, the user takes an image of lights mounted on towers with a camera and uses computer vision to estimate the position and pose of a user on the lunar surface, based on a priori information on the placement of lights. In this study, we put forward a design for the visual localization system. This includes the selection of appropriate cameras and the design for the placement of lights on the towers. We also develop software for identifying lighting cues and finding the user's position and pose in all six degrees of freedom (DOF). For validation, we perform hardware experiments using a scaled down model, in a sandbox we have constructed as a testbed for lunar construction operations. We then compare our results with pose estimation results obtained from fiducials, such as those proposed for pose estimation during in-orbit servicing. We expect that the method we propose can reduce the cost of hardware required for localization of surface assets on the moon.

E.1 Maximizing the Life and Utility of SmallSats in LEO Using a Network of Robotic Space Stations

Alton Zhang, Robert Wilkie, Jekan Thangavelautham
(SpaceTREx Laboratory, University of Arizona)

Thanks to rapid miniaturization in electronics, sensors, actuators and power systems, we have seen the birth of the smallsat technology revolution. This has led to the explosion of low-cost science and technology missions previously thought impossible. However, some major limitations exist within this paradigm, due to shortened lifetimes of the missions. This results in material waste, waste of launch spots and slower technology development cadence. Most CubeSat missions deployed in LEO only have an operational lifespan of one year or less, as they often do not carry enough propellant to revive their decaying orbits. Imagine the possibilities if these platforms could be retrieved and reused! Persistent platforms may be a solution to this problem. Persistent platforms are robotic spacecraft that are intended for longer missions, are autonomously assembled in space, and receive modular payloads. They will maintain their LEO orbit thanks to onboard propulsion and a regular refueling schedule. This reduces the economic costs of constant launches, enabling a “pay as you go” scheme. The modular payloads offer an interesting approach. If the payloads were smallsats and acted as modular components for the platform, these platforms could be serviced in space and change their objective and science instruments at a moment’s notice. In particular, the addition of payload spacecraft allows for persistent platforms to form an on-orbit virtual railway, where cargo and components can be exchanged. This leads to the concept of the on-orbit railway, with each of the persistent platforms acting as stations. This paper will examine the robustness of this concept in regard to damage mitigation. How does the system respond when several components become damaged over time and need to be replaced? Is there a state where the virtual railway system is unable to function, as too many components are in orbit? Is there an optimal cadence in transferring the component spacecraft? These questions will be examined with a series of experiments. A simulation will be created to examine the scenario at a larger scale, utilizing object-oriented programming to update the health of the station. This will be paired with a lower-fidelity physical model of the on-orbit railway.

E.2 Vision Sensor Aided Autonomous Mobility and Navigation for a Flatworm-Inspired Robot in Planetary Extreme Environments

Rebekah Cutler, Athip Thirupathi Raj, Eric Vazquez, Jekan Thangavelautham
(University of Arizona.)

As the frequency of landing on extraterrestrial bodies increases over the years, the potential for off-world exploration has also increased. From the iconic Touch And Go on the asteroid Bennu to Chandraayan 3 landing on the South pole of The Moon, we have successfully touched down on several different environments. This calls for the development of rovers that can efficiently traverse most, if not all such environments. This research paper introduces a novel robotic system designed to traverse a diverse variety of extreme environments inspired by the remarkable capabilities of marine flatworms. The Slugbot, drawing inspiration from the Velox robot, is equipped with adaptable rubber fins, effectively navigating terrains such as sand, ice, and water in its current version. The Slugbot's 3D-printed shell incorporates a range of sensors to gather crucial environmental data, while the control system coordinates the movement of 16 high-torque servo motors in a sinusoidal configuration.

This paper discusses the simulation and testing results of the traversal and navigation properties of the Slugbot in various environments. The primary objective is to evaluate and optimize the Slugbot for operation in low-gravity environments, making it adaptable to a wide range of space conditions. This adaptability will enable the robot to traverse polar ice caps, under-ice oceans, and sandy deserts, showcasing its versatility in extraterrestrial exploration. The Slugbot's exploration capabilities shall be fully autonomous, harnessing an AI vision sensor to discern the most favorable navigation paths through its surroundings. Ultimately, the project aims to enable the robot to reach areas that may be otherwise unreachable by any other methods, including conventional rovers,drones, hoppers, or remote sensing.

The equations governing the movement of the robot with respect to the 16 servos and the signals generated by the controllers have been identified, and simulations will be performed. We utilize a sandbox facility to test the traversal properties of the robot in sand with different traction coefficients and inclinations to identify the limits of the locomotion of the robot. Incorporating various sensors, such as the AI vision sensors, to map the surroundings to aid in navigation is discussed. In summary, this research presents an innovative approach to space exploration and navigation by developing a robot that draws inspiration from nature, particularly marine flatworms. The Slugbot signifies a significant advancement in creating adaptable and versatile robotic systems tailored for space navigation missions.

E.3 Design and Development of an Autonomous Sandbag-Filling Lunar Robot Margin

Chad Cantin, Siva Muniyasami, Jekan Thangavelautham
(University of Arizona)

The next step in space exploration is the development of a sustainable cis-lunar economy and, eventually, building lunar bases to support it. NASA Artemis and other international efforts are paving the way for it. Constructing infrastructure such as blast walls, shelters, and storage is the first step in establishing the lunar base. Current proposed methods for lunar infrastructure construction, such as 3D printing and molding, often involve significant energy consumption and complex machinery, resulting in high costs. While 3D printing is well-established on Earth, its effectiveness in the low-gravity lunar environment remains to be fully explored. Given the complexity and cost, there is a need for straightforward and cost-effective methods to build lunar infrastructure using ISRU materials on the Moon. We propose a sandbag as a building block for constructing the lunar structures. The lunar environment poses unique challenges for astronauts, including extreme temperatures and abrasive lunar dust. Robots offer a viable solution capable of operating in these harsh conditions without the same safety constraints as humans. Robots can perform complex and repetitive tasks in an efficient, timely manner, allowing for a significant reduction in human labor efforts and an increase in productivity. As automated robotic systems perform more strenuous labor, humans can tend towards exploration tasks and further lunar research. This work involves designing and developing an autonomous robot filling and bagging sandbags on the lunar surface. We explored and compared various sandbag-filling robots that could be modified and used for lunar construction. Further, we developed a small-scale prototype to test its efficiency of filling and bagging.

E.4 Design and Development of a Docking Adapter for Multi-robot Aggregation

Matthew Arcarese, Siva Muniyasami, Jekan Thangavelautham
(SpaceTREx Laboratory, University of Arizona)

Autonomous robots play a key role in exploration tasks in off-world environments such as Mars and the moon; sometimes, these robots are teleoperated by humans from Earth. Once humans go there and start to explore these environments, development projects such as building infrastructures, including storage and shelters, are crucial. Building and maintaining these infrastructures is a multifaceted task that requires several robots. For instance, constructing a sustainable landing pad on the lunar surface is critical. The first step would be the site preparation by leveling the surface; a single robot can easily get stuck as the lunar regolith is very fine. Additionally, In the context of off-world construction and maintenance, nominal and off-nominal tasks, such as moving supplies, cleaning chemical spills, firefighting inside the lunar base, and uprighting a fallen robot, may require assistance. Chaining multiple robots would be preferable to bolster the effectiveness of these tasks and enhance the robots' performance. A docking adaptor that allows these robots to connect and work together is designed and developed to achieve chaining. The docking adaptor consists of spherical gears that have been used to allow for the greatest freedom of motion while ensuring maximum rigidity of the joint while performing tasks on rough terrain. This design is analogous to a ball and socket shoulder joint. A quantitative trade study has been performed to evaluate the effective configuration of chaining to maximize the performance of the robots. In addition, smart sensor units embedded inside the docking adaptor provide communication between the robots, actuation, data transfer, and health monitoring. The docking adaptor allows for electrical communication between multiple robots to allow them to function as a unit and complete tasks that would otherwise be impossible for one. The design for the adapter will be comprised of five different models to determine the most effective design. Each model for the apparatus will incorporate different locking features and devices to keep the adaptor free from lunar dust and other lunar conditions. Each model will be tested on simulated lunar conditions to determine their robustness. Prototype testing for each model will begin with testing for structural integrity and its impact on robots' performance.

E.5 Multi-robot task planning for lunar construction using evolutionary algorithm

Adharsh Prasad Natesan, Siva Muniyasami, Jekan Thangavelautham
(SpaceTREx Laboratory, University of Arizona)

With the Artemis mission, NASA aims to not only take back humans to the lunar surface but also make a prolonged presence. As a result, there is a need for establishing semi-permanent and permanent lunar structures on the Moon surface. In order for the mission to be sustainable and reduce the transportation materials from earth, there is a notable emphasis on utilizing local resources, such as lunar regolith, as construction materials. Given the challenging lunar environment and practical difficulties of deploying astronauts, autonomous swarm of small robots could play a key role in lunar surface construction. Moreover, usage of few large, specialized robots designed for construction will increase the mission cost and at the same time difficult maneuver on the lunar soil due to wheel sinkage. Employing autonomous swarm of robots for construction comes with the need for building an effective strategy to not only perform the construction, but also to sustainably use the resources in the lunar surface. Moreover, as the robots work in a confined space while construction, it is important to devise a robust collision avoidance system amongst the robots, construction environment and humans. Thus, we propose an effective methodology for multi-robot coordination in lunar construction, aiming to reduce construction time and minimize collisions. The first phase involves the development of an effective task planning algorithm. To achieve this, we employ evolutionary algorithm-based methods to optimize construction sequences, ensuring a collision free and time-efficient building process. Though we formulate task planning strategies that minimizes collisions, the construction environment is dynamic, and lunar environment is unpredictable. Hence in the real-time execution phase, we implement a robust monitoring system for all robots involved in the construction activities. This monitoring system constantly assesses the robots' positions and trajectories. Based on the positions and trajectories, the possible collisions are predicted and proactively avoided. Further we simulated the results with various lunar structures and dimensions to test the effectiveness of the algorithms through the MATLAB environment. The synergy of the task planning optimization and real-time collision prediction-avoidance ensures not only enhanced construction efficiency but also a safer working environment for the multi robot systems.

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E.6 Power and Data Transfer with a Two-Stage CubeSat Docking Adapter

Nicolas Gross, Athip Thirupathi Raj, Jaret Rickel, Jekan Thangavelautham
(SpaceTREx Laboratory, University of Arizona)

With the rise in popularity of small satellites, such as CubeSats or nanosatellites, there has been a growing effort to enable small satellite servicing applications. By transitioning past the current communication and technical demonstration role that small satellites currently fill, many opportunities and solutions would become feasible. Example servicing and transfer applications include increasing the limited lifespan of small satellites, given their restricted power capacity, facilitating technology and software upgrades, allowing for the cleaning and removal of space debris, and providing mission flexibility. Power and data transfer specifically support the operation and maintenance of several subsystems, including sensors, instruments, and communication devices. Interplanetary missions could be supported by the maintenance and servicing capabilities offered by small satellite power and data transfer. For example, power could be transferred between a satellite equipped with solar panels, to another satellite that may lack power generation, or has been damaged, and requires supplemental power. If the satellites are large, a small satellite could be transferred between the two, carrying power from one to the other. This would lengthen the duration of the interplanetary mission without needing to send additional satellites that may not be able to travel the long distance in the required time. The development of servicing and transfer capabilities for small satellites is necessary for their future role in the constantly evolving space environment.

We propose a two-stage CubeSat docking adapter with integrated power and data transfer capabilities. For the soft capture stage, the adapters utilize a modified cone and probe geometry designed to correct for rotational and translational misalignment. Shape Memory Alloy (SMA) spring-loaded latches are used for locking and unlocking during and after the hard capture stage. Power and data transfer are facilitated through pogo-pin connectors. These connectors allow for a secure connection regardless of orientation, which is necessary as the adapters allow for docking in four unique orientations. Various connector options were explored, supported by a trade study that identified the optimal connector aligning with the design and mission requirements.

This presentation details the design, analysis, fabrication, and validation involved in creating a two-stage CubeSat docking adapter with integrated power and data transfer capabilities. 3D simulations and analytical calculations were used to develop prototypes for thorough testing in a controlled laboratory environment. Through this testing, limiting conditions are established, considering factors such as misalignment limits and maximum transfer rates. Validation is performed using ground-based systems, including 6-DOF robotic arms emulating spacecraft ADC systems and air tables to replicate the frictionless environment in space. The primary goal is to demonstrate a seamless docking scenario, including power and data transfer between two CubeSats equipped with metal 3D-printed docking adapters. Through this demonstration, the functionality and feasibility of the proposed docking and transfer system are shown.

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F.1 Smallsat-aided Mission for the 2029 Apophis Rendezvous: ATENA

Biagio Cotugno*, Michael Amato**, Eleonora Ammanito***, Carlo Burattini*, Giorgio Saita*, Valerio di Tana*

*(*Argotech S.r.l., **NASA Goddard Space Flight Center, ***Italian Space Agency)*

The impending close flyby of Earth by the Apophis asteroid in April 2029 offers a unique opportunity for advancing planetary defense and deepening our understanding of Near-Earth Objects (NEOs). The ATENA (Advanced Technology Exploration of NEA Apophis) mission, a collaborative effort led by the Italian Space Agency (ASI), NASA/GSFC (Goddard Space Flight Center), and ARGOTEC, aims to leverage international expertise and cutting-edge technology to achieve key scientific and planetary protection objectives. To enhance the planetary protection program, ATENA seeks to improve our knowledge of NEOs, with Apophis serving as a primary focus. The mission will utilize a microsatellite platform to achieve an interplanetary transfer to Apophis in under two years. A kick-staged mission is being considered for optimal trajectory, ensuring a positive C3 when departing Earth's sphere of influence. The satellite will feature steerable solar arrays, crucial for continuous power generation required for prolonged -thruster firing. Without the ability to rotate the solar wings, indeed, the satellite would be unable to fire thrusters during periods when the Sun does not illuminate the panels directly, hindering its ability to reach the asteroid. Navigating uncertainties in Apophis' shape and rotation state pose a challenge, leading the mission to adopt optical navigation. The spacecraft architecture, based on ARGOTEC's Hawk Platform, incorporates as key technologies an electric propulsion based on Xenon and a UST-Lite X-band transponder. The payload suite, including the LICIACube cameras (LUKE and LEIA) and NASA/GSFC's BIRCHES infrared spectrometer, significantly enhances the scientific capabilities. BIRCHES expands the spectral sensitivity range up to 4.2 μm, providing comprehensive observations of Apophis' surface features and volatile-related characteristics. The international collaboration between ASI, NASA/GSFC, and ARGOTEC plays a pivotal role in the mission's success. Building on ARGOTEC's experience with the LICIACube mission, NASA/GSFC contributes the BIRCHES instrument and operates Osiris-Apex, complementing ATENA's objectives. ASI serves as the coordinating force among stakeholders, ensuring effective collaboration and mission coordination. In conclusion, ATENA represents a pioneering effort in asteroid exploration and planetary defense, pushing the boundaries of technology and international collaboration. By addressing challenges, employing innovative strategies, and leveraging the strengths of each collaborator, ATENA aims to advance our understanding of NEOs like Apophis and demonstrate rapid-response capabilities crucial for future planetary defense scenarios.

F.2 Terrarium Controller to Imitate Lunar Conditions for Live Organisms

Aleksandar Antonic, Claire Pedersen, Jekan Thangavelautham
(University of Arizona)

Understanding the ability of organisms to survive in space is essential for our plans to return to the Moon and eventually travel to Mars. Food and nutrition are among the many other requirements that astronauts must meet to survive in space. Testing which plants can survive in various extraterrestrial conditions is necessary to ensure the survival of manned missions. A 12U CubeSat terrarium controller that will simulate lunar conditions is proposed to perform these tests. The CubeSat will also possess a 2U terrarium payload containing organic material that will need to be kept alive for the mission. Thus the controller will have two separate regions of interest: the simulated lunar conditions, and the conditions inside the terrarium. Thus the controller will possess two primary computer systems that will have limited communication with each other. The controller will be comprised of several computer sensors that will all capture information regarding both regions and make decisions both automatically and manually to ensure the homeostasis of the organism inside. This information includes but is not limited to temperature, pressure, humidity, and gas concentration. The sensors capture quantitative data, meaning that if falls out of a certain range, a signal will be triggered to ensure that the temperature falls back into the range. Any errors can be manually changed by entering a desired condition into the computer's communication link. A Seebeck and Peltier device, otherwise known as a thermoelectric generator (TEG), will accomplish this by heating and cooling the system as necessary. To recreate lunar conditions, the controller will be connected to a centrifuge to recreate the Moon's gravity as well as external TEG that will be set to the temperature extremes on the Moon (-150 to 120 ℃). The controller will report the information from both regions using a two-way radio transmitter that will send the data, as well as capture any signals that are sent to change the conditions of the CubeSat at will. Lighting is also a key factor in the growth of any plants, and an LED lighting system will be connected to the controller to imitate the presence of the Sun. This controller will ultimately demonstrate the ability of CubeSats to recreate lunar environments that can host future experiments.

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F.3 Ciclunar spacecraft assembly for near earth surveying

Adrien Bouskela, Athip Thirupathi Raj, Jekan Thagavelautham, Sergey Shakrayev, Leonard Vance

(University of Arizona)

Detecting Near-Earth Objects (NEOs) holds significance due to the dual threats and opportunities they present to Earth and space exploration. Identifying and tracking NEOs is crucial for planetary defense, allowing scientists to assess threats, develop deflection strategies, and mitigate risks. Near Earth Asteroids (NEAs) detection also aids scientific exploration, providing insights into the early solar system and contributing to our understanding of life's origins. Comprehensive surveys of the near-Earth environment also enhance space situational awareness, preventing collisions and improving traffic management. As scientific and commercial interests into the Earth Moon system and beyond grow there is a need for reliable and persistent monitoring of our neighboring environment.

We propose a truss-like structure as a robotic spacecraft assembly for the surveying and study of such Near-Earth Objects (NEO) as well as general sky surveying. The multi-agent system is in the majority constructed with standardized CubeSat spacecrafts with a deployable telescope as primary payload. Universal docking adapters enable on-orbit assembly and reconfiguration. The base concept is formulated around optical axes normal to a main rotation axis. Points of view are distributed over multiple angular positions such that the constant and steady rotation allows for large area coverage and short revisit times. Constructed from multiple CubeSats, the structure is inherently modular, extensible, and transformative with the ability to add, replace, or upgrade individual units. Its lifetime is only limited by the willingness to reconfigure it to meet the requirements for changing missions and objectives.

At the core of the system is the proposed design for a 16U CubeSat carrying a telescope that demonstrates significant advancements in system miniaturization, and overall increased efficiency by integrating relatively large apertures into the low-cost spacecraft standard. After deployment of the optical system a spacecraft can dock with the main assembly, contributing to the surveying mission as an additional broad-spectrum point of view or a dedicated narrow band follow-up device placed in sequence thanks to the structure’s rotation. Autonomous management can task a subset of spacecrafts to undock, de-rotate, reassemble, and focus their view on a high value target of interest, adding system versatility. Finally, the assembly system can serve multiple missions as units can be dedicated to specific fields of research beyond to primary use case, such as supernova detection. Overall fostering a lower barrier to access space based optical platforms and preparing for future opportunities and collaborations in space exploration.

F.4 Space Song Foundation: The Tree of Life

Julia Christensen*, Steve Matousek**, Roger Klemm**, Alessandra Babuscia**, Joel Ferree***
*(*Oberlin College, **Jet Propulsion Laboratory, California Institute of Technology, ***Los Angeles County Museum of Art)*

Space Song Foundation President Julia Christensen will give a project update about The Tree of Life, a global art project comprised of living trees on planet Earth in communication with a CubeSat in LEO. The Space Song Foundation is currently working on a semi-permanent tree-antennae at the Center for Land Use Interpretation's Desert Research Station in the Mojave Desert, which will be featured in the upcoming Pacific Standard Time exhibition produced by the Getty Institute in Los Angeles.

The Tree of Life connects Earth and outer space through a song, which is sent via radio waves between an orbiting spacecraft and an unlikely technological component: a set of live trees that have been activated to operate as large, living antenna systems. The trees and spacecraft will sing a song to each other continuously for centuries, and it will be recorded in real time for 200 years. The song is formed by collecting long-term data sets and sonifying that data using custom software. The data-sounds describe the trees' experience of life on Earth (light, soil moisture, and temperature); the spacecraft sings a song describing its own long-term operational capacity (energy, velocity, communication bandwidth, etc.). The numbers in these data sets are translated into sonic frequencies and communicated between the trees and spacecraft via radio, so that ultimately, the trees and spacecraft sing a duet for 200 years. The song is open-source and accessible to the public; DJ's can re-mix it, and scientists can use it to detect shifts that can be difficult to glean from centuries-long data sets.

In this presentation, Christensen will present the software used for the data sonification, and updates about the ground stations and CubeSat. At the organization's table, we will present demos of the sonification system and have our upcoming record to listen to on-site. We will also have materials related to the project available for people to take with them, to broaden the collaborative conversation.

F.6 SUMS: Supporting a Uranus flagship Mission with SmallSats

Dylan Barnes, Paula do Vale Pereira
(Florida Institute of Technology)

Following recommendations from the 2023-2032 Planetary Science and Astrobiology Decadal Survey, we propose a novel pre-phase-A level Uranus exploration mission centered on using swarms of small spacecraft to observe the Uranus system. This mission could support the Uranus Orbiter and Probe detailed in said Decadal Survey, acting as a supplemental to the flagship level mission. We propose launching a 3,200 kg spacecraft on a Jupiter-Uranus gravity assist transfer trajectory with a transfer time of six years, having the spacecraft arrive at Uranus in 2039 after launching in 2033. This shorter transfer and accelerated development timeline would allow for an earlier arrival date than a traditional flagship spacecraft, which would make it possible to observe the changing of the Uranian seasons from solstice to equinox, helping us better understand the atmospheric dynamics. To maintain the quality of data collection while minimizing mass, we propose that the spacecraft will be composed of a carrier spacecraft with a 2,562 kg wet mass, which would be used primarily for communications and orbital transfers, and a swarm of CubeSats with a combined wet mass of 640 kg, which would house the instrumentation. The swarm of 16 CubeSats of approximately 40 kg each would be divided into 4 groups of 4 identical spacecraft. Each group will be equipped with specialized instrumentation, exploring Uranus more extensively and from multiple angles simultaneously. This spatial distribution of the instrumentation would allow for measurements that require multiple perspectives of observation, such as radio occultation and precision gravity measurements. This research demonstrates that a high-level analysis of such a deep-space small satellite mission converges into a viable solution and invites experienced professionals to join the idea and perform further validation of the concept.

F.7 Global Mapping of Lunar Surface Water and Hydroxyl in Context

Timothy A. Livengood*, Pamela E. Clark**, Tilak Hewagama***, Eric Kan***, Clifford K. Brambora***, David C. Bugby****

*(*University of Maryland, **Morehead State University, ***NASA Goddard Space Flight Center, ****Jet Propulsion Laboratory, California Institute of Technology)*

We present a concept for a small spacecraft mission and instrument to map the location of water everywhere on the surface of Moon and to determine its physical and chemical state, whether it is in the form of hydroxyl ions, molecular water, mineral hydrates, or ice. Advances in several technologies, including detectors, cryogenic cooling systems, and small spacecraft infrastructure, enable a long-lasting global mapping mission from a specialized small spacecraft platform. The mission employs a compact hyperspectral instrument to map surface reflectance and thermal emission over the wavelength interval 2.5–12 µm with a target spatial resolution of 1 km. The instrument will capture three spectral features of water, at 3 µm, 6 µm, and 11 µm, as well as features identifying silicate minerals and the surface temperature from long-wavelength thermal emission for context, co-located on the same spatial scale. A long-duration mission of greater than 6 months in polar orbit enables mapping the entire surface at multiple times of day to determine the diurnal variability of each spectral feature in the context of the host mineralogy and surface temperature, identifying the phase of the water, abundance of surficial H2O vs. OH and the conditions in which it is located. Several mechanisms have been proposed for the apparent diurnal variability of surficial water, including: horizontal transport to local cold traps (shadows) or the global cold trap of the night side; destruction and re-formation of molecular complexes; and competition between delivery of hydrogen from solar wind implantation and removal by photolysis and transport in the heliospheric magnetic field. By mapping the spatial distribution and diurnal cycle of water species over the entire surface, the chemical state of surficial water and the mechanisms for delivery, transport, and removal will be tightly constrained.

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G.1 Origami Solar Arrays for Small Space Systems

Nathaniel van der Leeuw, Anna Dinkel, Jekan Thangavelautham
(SpaceTREx Laboratory, University of Arizona)

Space system miniaturization has gained traction in recent years. Large-scale space flight is costly as launch costs are expensive for high mass and volume. CubeSats and small-scale rovers are far less costly to develop and launch but must operate off small-scale components. An efficient means to supply power for these small-scale missions is needed, both in orbit and extraterrestrial environments. Recent research utilizes flexible solar arrays for small systems as conventional Silicon panels are too heavy. Rapidly expanding and contracting polymer-based solar panels have been developed using straightforward mechanical systems, but they are easily wrinkled over time or torn through by dust particles. New small-scale missions based upon these super thin technologies must be simultaneously rigid yet compact.

Origami allows for a small, storable system to expand in space while maintaining rigidity. There are two mainstream methods of creating a compact solar array utilizing origami. The Hannaflex design uses a Hoberman ring to expand from a compressed cylinder to a disk-like shape. As the ring expands radially outward, a sheet of silicon-based panels is exposed, allowing for much of the surface area to be contained in the folds. However, it requires a heavy metal skeleton that uses a complex system of motors to expand the design. The Ultraflex design has a lightweight mechanical structure that creates an umbrella from a compressed wedge shape. The wedge uses tension to rotate, expanding the system. Unfortunately, the system is never fully compressed, leaving room for debris to cover the surface. Small-scale missions require a solution that minimizes both volume and mass.

We propose a doughnut origami design using lightweight perovskite solar arrays for small-scale rovers and satellites. Inspired by the Yoshimura pattern, it uses isosceles triangles to create a cylindrical surface that rapidly expands upward. When a force is applied to the center of the cylinder, the triangles temporarily compress to absorb the force while maintaining structural stability. The interior of this surface is hollow, allowing for the placement of perovskite cells across the exterior and interior of the design. The array minimizes both packaged mass and volume, suitable for small lunar or interplanetary rovers and small satellites. The rigidity of the cylindrical structure can withstand strong winds and ragged dust particles characteristic of Mars. The design exposes the exterior and interior space to generate the largest amount of power for small-scale missions.

G.2 Inflatable Shelter for Extraterrestrial Protection

Andrea Torres, Anna Dinkel, Jekan Thagavelautham
(SpaceTREx Laboratory, University of Arizona)

NASA suggests humans will be on the surface of Mars by the 2030s. Much of the Martian surface is yet to be explored. Mars rovers must be robust enough to handle extreme temperatures, harsh radiation, and severe wind and dust storms. Launch costs are expensive for large and heavy space vehicles. Using small systems can lower costs, allowing for more missions and further surface exploration. However, these smaller systems must still be able to withstand Mars's surface conditions.

We propose an inflatable shelter for Martian explorers that protects rovers from dust storms, radiation, and extreme temperature fluctuations. Inflatable technology allows for compact and lightweight packaging and is the perfect addition to small rovers exploring the Martian surface. Rovers enter the garage to escape extreme surface conditions. The system utilizes hydrophobic, dust-repelling materials, cleaning brushes, and dust mitigation plates to clean off the rover and sensitive instruments. The walls insulate and regulate the internal temperature of the shelter for the rover. Additional benefits such as data storage and backup, charging, and communication are available to the rover, increasing system redundancy and failure mitigation. This technology enables small-scale rovers to be robust enough to effectively explore the Martian environment.

For future human exploration, this design also acts as a proof of concept for airlocks and internal pressurization for Martian habitats. Inflatable technology is often suggested for use in Lunar and Mars habitats, as it can be compressed tightly for launch and expanded to large volumes once on the surface. It can be designed to be internally pressurized, which is necessary for future human astronauts operating on the surface. Pressurizing the internal inflatable shelter allows us to verify this technology before testing with humans, reducing overall risk.

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G.3 High Frontier: A Low Thrust and Autonomous Navigation Mission for Near-Earth Asteroid Excavation

Dianna M. Velez, Lisa Whittle, Kalle Anderson, Dale Howell, Daynan Crull, Lauri Siltala
(Karman+)

Karman+ is a U.S.-based startup seeking to make asteroid mining a reality. As the first step towards that goal, we are currently developing a SmallSat sample-gathering mission, named High Frontier, to a near-Earth asteroid. Launch is planned for the fourth quarter of 2026 with the primary mission objective of multi-kilogram scale sample extraction from the asteroid's surface. The talk will discuss the overall concept of High Frontier, its development process including tools, challenges faced, research areas, and company goals.

The spacecraft will use solar electric propulsion (SEP) to perform its Earth escape spiral and interplanetary cruise. To reduce dependency on ground communication resources, during cruise the spacecraft will perform optical navigation which will be processed by an autonomous navigation system. Once at the asteroid, the spacecraft will map the asteroid in stages from station-keeping positions. An onboard map will be developed in support of simultaneous localization and mapping (SLAM). A brief "touch and go" (TAG) maneuver will be performed to extract a sample of several kilograms from the asteroid. Afterwards, the spacecraft will return to its safe station-keeping position to downlink the results.

Karman+ takes inspiration from multiple prior and ongoing missions for scoping key technology and concept of operations. In particular, the missions Deep Space 1, Hayabusa, Hayabusa2, OSIRIS-REx, and Psyche offer lessons for High Frontier to reduce risk while advancing the state of the art. The aspects of each mission Karman+ is drawing from will be briefly described in support of the High Frontier rationale. Highlighted will be areas where Karman+ has chosen to deviate from these prior missions.

For the Karman+ asteroid mining operations to reach eventual profitability, the target asteroids must be reachable both in terms of delta-V and time of flight to minimize spacecraft mass and operations duration. Karman+ has done considerable work determining potential target asteroids for mining operations. Now Karman+ is building up additional capability to design solar electric propulsion trajectories, analyze optical navigation techniques, plan asteroid proximity operations, and increase analysis fidelity generally. Tools which will be detailed include MONTE covariance analysis and its trajectory design tool MCOLL, Blender, Sedaro, and others. Karman+ is in the process of down-selecting components and focused on commercial off-the-shelf (COTS) devices.

The aim of the talk is to raise awareness of the High Frontier mission for potential collaboration and partnerships, solicit feedback, and increase support for independent SmallSat near-Earth asteroid missions.

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G.4 A Novel Excavator for an Asteroid Mining Context

Korbin Hansen, Siva Muniyasamy, Jekan Thagavelautham

(SpaceTREx Laboratory, University of Arizona)

Asteroid mining is a promising means to facilitate the in-space production of propellants and precious metals. As developing the space economy will enrich Earth and expand humanity's reach, there is a push to make asteroid mining technologies more feasible. In this paper, several continuous mining tools are physically tested to inform the design of an optimized, scalable, asteroid-specific excavator. These tools are designed to meet the unprecedented challenges posed by the asteroid surface environment—microgravity, where even minute reaction forces can translate to a loss of stability or scatter regolith to escape velocity; lack of cohesion, making it difficult to remain secure while mining; and (relatively) large grain sizes, which may obstruct machinery. Bucket wheel and pulse elevator designs are considered. Bucket wheels have been incorporated into the most technologically mature Lunar mining vehicles, such as NASA's ISRU Pilot Excavator. Bucket wheels provide a solid foundation for an asteroid-specific excavator, though fundamental redesigns are necessary. A pulse elevator employs a vibrating assemblage of scoops to vertically translate granular materials, such as low-cohesion asteroid regolith. Testing these excavators necessitates the development of a simulant that is mechanically analogous to asteroid surface conditions. When the constraint of affordability is applied, the resulting simulants are to be composed of shredded foam particles. By employing multiple sieves, simulants of varying average grain sizes can be developed in parallel. Since foam particles will not precisely match asteroid surface conditions, each batch of simulant will be mechanically tested for cohesion, angle of internal friction, density, and porosity such that scaling factors can be obtained. As Bennu is the most thoroughly examined rubble pile asteroid—courtesy of the OSIRIS-REx mission—it will be considered representative of asteroid surface conditions for comparison. Next, 3D-printed prototype excavators are tested for each grain size configuration—the test beds will read horizontal cutting force, vertical resistive force, deployment angle of extended components, electric power consumption, and filling efficiency. Resolved force data is compared to the weight and resulting friction generated by the excavator if it was placed on Bennu. Deployment angle will be fed into computer simulations to determine the handling characteristics of the bucket wheel in the irregular terrain native to asteroids. Electric power consumption and filling efficiency will be used to determine the energy required to mine a set mass of regolith, which is critical information for top-level systems engineering or economic analysis.

G.5 Experimental Investigation of Rotor Model with Blowing Jets

Elijah Greenfield, Emerson Moser, Parisa Footohi, Sergey Shkarayev
(University of Arizona)

Maneuvers of helicopters and tiltrotor aircraft cause rapid variations of angle of attack, flow separations, and dynamic stall on rotor blades. These fluid dynamics phenomena are highly unsteady and three-dimensional. Active flow control methods employ jets in spanwise and chordwise directions of blades to mitigate negative effects but add more complexity into the flow physics. In this experiment, active flow control of a rotor model in a wind tunnel is analyzed.

The rotor assembly used is comprised of two NACA 0012 rotor blades with a channel along the quarter chord, allowing a jet of air to extend through the blade tips in the spanwise direction. The rotor configuration used for this experiment included a 6° angle between the rotor cylinder and mounting rod and a 12° angle between the blades and rotor cylinder.

The rotor model was tested in the Arizona Low Speed Wind Tunnel. Particle Image Velocimetry (PIV) was utilized to capture images of the clockwise-rotating blade at four different angles relative to the freestream. To collect data, an sCMOS camera was used in conjunction with a Class 4 PIV laser. The laser illuminated the blade at the quarter chord on both the top and bottom surface, with the laser sheet being at the same pitch angle as the blade. The camera was oriented to focus on the tip of the blade from the trailing edge, oriented normal to the laser sheet. PIV software was configured to take a set of 100 image pairs, using the time difference between frames to determine a velocity field for the test.

Results were found to be consistent across the range of angles. In the baseline cases, the flow can escape around the tip and flow from the bottom to the top of the blade. This flow continues curling inward along the blade, reducing the spanwise velocity close to the tip. The curling of the flow results in the formation of tip vortices, which propagate backwards in the flow as the blade moves. The activation of the tip jets results in a reversal of this spanwise flow, with velocity increasing drastically just past the tip of the blade. The air on both the top and bottom surfaces of the blade is entrained as the jet is activated, increasing the spanwise velocity. The vortex core is also pushed outward and upward, further diminishing the tip vortex's capacity to affect the flow over the blade.

G.6 Enabling Deep Space Exploration Using Inspectors Accompanying Small Spacecraft System of Systems Architecture

Kargi Chauhan, Athip Thirupathi Raj, Jekan Thagavelautham
(SpaceTREx Laboratory, University of Arizona)

The aerospace industry has widely adopted small spacecraft thanks to the miniaturization of electronics, sensors, actuators, and power systems. Thanks to these advancements, we see increasingly ambitious missions to explore the four corners of the solar system. These new exploration targets will require small satellites to travel further and faster, communicate at higher bandwidths, and operate longer. Achieving these target capabilities with miniaturization alone will be challenging. Here lies the opportunity for multiple modular small satellites to be assembled to form a structured system of systems. This aggregation of small spacecraft can enhance required redundancy, increase range and velocity, enhance communications, and achieve long mission life. The challenge, however, is to develop a robust yet reconfigurable system of systems architecture.

Given that these crafts will be operating far away from Earth, they will need to operate autonomously and handle unexpected mission scenarios. A key enabler for this aggregating architecture is its ability to be dynamically reconfigured based on needs. In response to these challenges, we are evaluating vision-based machine learning methods to simplify depth perception, navigation, and manipulation in 3D workspace using monocular cameras. The conventional approach to depth estimation involves either the use of multiple cameras, such as the case in motion capture in movie studios, or the use of costly and time-consuming techniques, such as human-in-the-loop interventions or deployment of large equipment with the use of inspector spacecraft outfitters with single vision sensors.

Singular vision sensors pose difficulties in space, especially for spacecraft for attitude estimation, since it becomes more challenging to estimate the target spacecraft's pose (position and orientation) over image sequences and to determine the state space of the target spacecraft module. Finding and calculating the target spacecraft module's pose and velocity using monocular image sequences will be a key milestone in this approach. For these reconfigurable deep space travelers, we envision they would carry a small fleet of miniature inspector spacecraft. This is akin to deep sea whales or sharks accompanied by a remora fish that removes parasites from the mouth and skin of these larger creatures.

Each inspector spacecraft could be a CubeSat, such as a 3U CubeSat (30 cm × 10 cm × 10cm). We propose the use of Machine Learning Algorithms such as Convolutional Neural Networks (CNNs), Recursive Neural Networks (RNNs), Autoencoders, and Random Forest Regressors, which are tailored to the exact specifications of these spacecraft inspection missions.

The project will employ a multifaceted approach incorporating innovative technologies, such as computationally efficient frameworks, simulated settings, and computer vision algorithms with convolutional neural networks (CNNs), which allow generating bounding boxes around the target spacecraft to detect and pinpoint them within the photos. Then, pose estimation is applied, which can then be used to detect image sequence changes in the position and orientation of the target spacecraft concerning the inspector spacecraft camera. This is vital information for an accurate inspection. The training and validation data ranges from simulated synthetic data to real-world test data from lighting-calibrated test facilities. Working in simulated situations enables generating algorithms to undergo extensive testing and validation. Testing the generated algorithms in real-world situations guarantees their resilience and efficacy. Maximizing the hardware resource utilization ensures accurate range and efficient processing, two things necessary to successfully complete inspection tasks in an interplanetary environment.

G.7 ACORN: the Advanced Compact Orbiting Radar for luNar sounding

Stefano Nerozzi*, Jack Holt*, Mary Knapp**, Lenny Paritsky**

(University of Arizona, MIT Haystack Observatory)

NASA suggests Orbital radar sounding at meters-scale wavelength is a unique geophysical tool that can address many objectives in lunar science and exploration by probing the subsurface to depths and resolutions that prior imaging and sounding radars cannot reach, with global-scale coverage that landed platforms cannot achieve. These objectives include the distribution of ice in the subsurface to hundreds of meters of depth, the nature and depth of regolith and megaregolith, the characterization of mare basalts and detections of lava tubes, and three-dimensional context for landed missions with in-situ instrumentation.

The number of flight-proven instruments for radar sounding is currently limited to a few examples based on conventional technologies with inherent limitations, both in terms of mass/power/volume and performance. There is a need for compact radar sounder technology that can be deployed from a small volume - suitable for both dedicated CubeSat/SmallSat missions and as part of an instrument suite on a larger spacecraft. Such a radar must provide fully polarimetric information for the identification of subsurface ice and have directivity to determine the source of echoes. This helps prevent the misidentification of off-nadir surface echoes as true subsurface echoes. Conventional technology requires very large antennas precluding a small form factor and limiting the options for mission scenarios.

The Advanced Compact Orbiting Radar for luNar sounding (ACORN) will be based on a vector sensor antenna (VSA), a transformative solution for radar sounding with the potential to address many limitations of current technology. This is due to its measurement of all components of both the electric and magnetic fields of electromagnetic wave echoes. These data enable determination of polarization and angle-of-arrival for multiple discrete sources using just a single small payload. These are key aspects in the ability to generate a fully-polarimetric, high-resolution subsurface mapping radar that operates across wide frequency bandwidths.

ACORN and its VSA are compact and deployable from a 4U volume, enabling the possibility of a complete radar in a small package. It is a novel approach to providing spatial resolution and penetration that provides a new alternative to distributed arrays of elements or large directive apertures for radars. Leveraging heritage from NASA's AERO-VISTA mission to develop and launch a Cubesat VSA for passive (receive-only) study of the radio aurora, our VSA technology is now sufficiently mature to develop an active VSA-based radar with a small form factor and performance that addresses a range of planetary radar applications.

G.8 CLEW (Compact Lunar Explorer for Water): State of the Art IR Spectrometer for a Lunar Cubesat Orbiter

Pamela E. Clark*, T. Hewagama**, T. Livengood**, C. Brambora**, E. Kan**
(Morehead State University, NASA Goddard Space Flight Center)

During the last year we have developed a concept for a follow-on to BIRCHES, a low cost, compact 2.5 to 12.5 micron range IR spectrometer, CLEW, that fits within the next lunar (12U) Cubesat payload constraints. CLEW has modest increases in SWAP parameters (approximately 25%) relative to BIRCHES, yet consists of high heritage components with greatly advanced capabilities in sensitivity, spectral coverage, and less active cooling demand at comparable wavelengths [e.g., Althobaiti and al-naib, 2020]] as exemplified by the Compact Thermal Imager (CTI) [Jhabvala et al, 2010, 2019], which utilizes a Type II Strained Super Lattice detector combined with the ACADIA processor, follow on to the OVIRS SIDECAR ASIC [Loose et al, 2018; Jennings et al, 2022]. Although initially developed for astronomical applications, the CTI has already been modified for lunar surface applications as the Compact Lunar Hydration and Mineralogical Explorer (CLuHME) [Bower et al, 2022] with the incorporation of a Ricor 508 or later model cryocooler in an IDCA configuration. Limited bandwidth (still <256 kb) precludes configuration as an imaging spectrometer, but our readout design is configured to allow spatial resolution (approximately 1 km) within our 10 x 10 km field of view. CLEW would also have an internal calibration source. A Cubesat contextual camera in 'density slice' mode could be added to assist in position determination by matching crater distribution patterns and the terminator position.

H.1 Conceptual design of unpowered glider for soaring flights in the Martian atmosphere

Owen Sutherlin, Miguel Coronado, Stevie Robbins, Adrien Bouskela, Sergey Shkarayev
(University of Arizona)

For decades, humanity's exploration of Mars has been confined to locations easily accessible by wheeled rovers, which are limited by their ground-based nature and relatively slow pace of travel. While these rovers are invaluable for scientific research, they are physically unsuited to access especially rugged terrain, such as canyons and steep craters. However, a solution was demonstrated by the Ingenuity rotorcraft, proving the feasibility of aerial exploration of Mars and leading to a rise in proposed aerial missions, including the development of gliders. Powered by wind patterns for sustained flight, they present an incredible opportunity to traverse previously unexplored and unreachable areas at minimal energy costs.

The versatility of a long endurance glider can bring remote sensing equipment to regions such as high mountains and deep canyons. The present work proposes a glider design that enables measurements of mass and ionic compounds and their relative abundance, supporting planetary science and the search of past or present life. Beyond reaching remote locations for remote sensing, the proposed glider supports atmospheric research with both the navigation instruments and its payload. Together they enable measurements such as relative humidity, atmospheric pressure, air temperature, magnetic environment, and in situ measurements of the size distribution and concentration of airborne dust particles on the Martian surface. This would have a strong impact on the understanding of climate and aeolian processes on Mars and support research efforts into the "Adapting to Space" and "Living and Travelling in Space" science objectives outlined in the most recent Decadal Survey.

The proposed glider design is structured around a 6U CubeSat frame for ease of integration of flight instrumentation, power management systems, and scientific payload. This core fuselage component is encased in an aerodynamic shell. Referred to as a blended wing body, this design increases aerodynamic efficiency through optimizing the lift distribution across its entire airframe. The characteristics of the resulting flying wing are studied to select appropriate sizing and wing sweep parameters, with a focus on stability and aerodynamic efficiency of the aircraft. Flight on Mars is challenged by its low density, which leads to flow conditions with high Mach and low Reynolds numbers. Although existing literature on such flow conditions is limited, a thin airfoil with reflex is proposed as a feasible solution. The resulting design is presented as an advancement in the Mars sailplane concept for exploration of the Martian atmosphere and rugged terrain.

H.2 Exploring the Martian canyons by means of atmospheric energy harvesting

Adrien Bouskela, Sergey Shkarayev
(University of Arizona)

The use of aerial vehicles for planetary exploration of Mars was successfully demonstrated by the Ingenuity helicopter, paving the way for future missions to push past existing limitations to scientific return. Existing spacecrafts often restrict themselves to terrain favorable to available Entry Descent and Landing (EDL) technology. Yet aircrafts can forgo the last step of EDL and deploy to previously unreachable regions of high interest such as canyons and high ridges. For such targets, science can be returned at minimal to no energy cost by gliders utilizing a technique known as soaring. By maneuvering within variable airflow regions energy is harvested from the atmosphere, enabling a purposely designed glider to achieve extreme endurance without the need for propulsion.

Previous research has shown that Mars's near surface planetary boundary layer has substantial and persistent wind flows driven, in part, by the high daily thermal changes. Both are advantageous to soaring with temperature changes leading to ascending airflows highly favorable to static soaring. Wind around ridges cause shear layers, regions of significant vertical changes in horizontal air velocity. On earth such flow structures have been utilized for dynamic soaring, a cyclic flight pattern that harvests energy through repetitive crossing of the shear region, increasing available flight energy over time.

The energetics of dynamic soaring have been studied and showed that such flight is possible on Mars, where numerical modeling found substantial winds in regions such as Valles Marineris. The present work introduces solution flight paths for Mars such as (1) straight line ascending and descending, (2) fixed circular paths inclined to the horizontal, and (3) spiraling ascent and descent along a helical path. Together they form the fundamental flight paths for accumulation of kinetic energy through circular flight, gains of potential energy by means of static soaring, and traveling at no energy cost through wind riding. Numerical solutions are obtained for each technique given a Mars glider and typical Mars conditions. Results show significant amounts of energy gains and support the construction of a proposed comprehensive exploration mission.

H.3 Improving Wind Model Profile for "1-cos" Discrete Gust

Kylar Nietzel, Sergey Shkarayev, Paul Dybskiy, Adrien Bouskela
(University of Arizona)

There is increasing interest in air vehicles for planetary exploration with numerous rotor and fixed wing aircraft being proposed in light of the accomplishments from the ingenuity helicopter. For airframe reliability under varying environments, it is important to consider the aeroelastic effects because they affect the aerodynamic performance, maneuverability, and control of a spacecraft. All these factors will cause peak aerodynamic structural loads. Therefore, the design of a new spacecraft for planetary exploration should consider the effects of wind gusts to assure reliability and stability. Such missions target the atmosphere of Mars, Venus, and Titan where the effects of sudden variations in airflows can't be ignored, yet facilities to produce controlled gusts at low Reynolds number are limited. There are two models to describe atmospheric turbulence defined in the FAR and CS: a continuous model and a discrete model. For extreme turbulent cases, the discrete model is defined to be a "1-cos" shape. To model a synthetic wind gust, oscillating vanes are placed at the inlet of the test section and possess a symmetric airfoil. These vanes are actuated with a time-varying oscillation and induce a vertical component into the freestream which propagates down the test section. Oscillating vanes have been proven to be the system of choice for gust generation because of its repeatability, so multiple tests can be conducted under the same gust conditions. Creating an artificial "1-cos" gust profile is the focus of this research. Following literature, the constructed system consists of composite vanes, mounted on bearings, and actuated by servo motors. The input to the system is angular vane positions with respect to time. The generated gust (the output of the system) is measured with a two-dimensional hot-wire probe situated downstream where future spacecraft models would be mounted. Preliminary results revealed that a "1-cos" vane angle function produced undesired characteristics in gust response. Literature suggests that a more complex parametrically defined angle-time function is required to minimize these characteristics. Based on iterative wind tunnel experiments, the parameters for this new input function were identified for different flow velocities and gust parameters. A motor input to gust output was established for a specific range of desired gust amplitudes and gust frequencies, thus completing the commissioning of the low-speed wind gust generator at the University of Arizona. Finally, this work will present this gust generator as available for the comprehensive study and development of future atmospheric spacecraft designs.

H.4 Train of Autonomous Aerial Vehicles for Subterranean Exploration with SLAM Capabilities

Nicolas Blanchard, Amber Parker, Arturo Lopez Jr, Sergey Shkarayev, Abhijit Mahalanobis
(University of Arizona)

Autonomously operating unmanned aerial vehicles (UAVs) are vital for exploring unknown spaces. Search and rescue missions, building exploration, surveying, reconnaissance, and extraterrestrial exploration all benefit from a robust system of autonomous vehicles. This work realizes a system of autonomous vehicles for exploring caves and lava tubes while addressing the challenges of GPS-denied navigation, low light conditions, intricate branching structures, rock formations, and other obstacles.

Previous publications have outlined localization and mapping methods to execute GPS-denied navigation inside unknown environments. LiDAR and onboard cameras are often used in a SLAM (Simultaneous Localization and Mapping) algorithm to create real-time pose estimation. Our conceptual system employs a visual-inertial SLAM (viSLAM) algorithm for localization alongside a lightweight Time-of-flight (ToF) camera for 3D mapping. Consequently, robust localization and dense 3D geometry maps can be generated without needing a traditional 360-degree scanning LiDAR sensor.

The realized system operates with multiple vehicles exploring in a train configuration, with the front vehicle leading the train and the other vehicles following the leader's path. At the entrance to the cave, a ground station computer parses video feed from the train and uses a DCNN object detection algorithm to direct the train toward the cave entrance.

Visual-Inertial Odometry (VIO) data from the viSLAM algorithm enables drone navigation, providing real-time position and orientation estimates without relying on GPS signals. In the VIO ecosystem, vibrations pose a significant challenge to localization accuracy, causing drift and instability. Vibration-dampening measures are implemented and flight parameters are fine-tuned to mitigate these effects and ensure reliable localization in challenging environments.

A drone mounting system is utilized to carry a headlamp for illuminating dark environments during autonomous flight. The mount is 3D printed and designed to allow for both optimal lighting angle and vibration isolation. This system is essential for the VIO aspect, which relies on clear visibility to determine the drone's position. To mitigate the mechanical vibrations introduced by the addition of the lamp mount to the airframe, nuts, bolts, and vibration rubber dampeners are used to secure the mount tightly.

Ongoing testing demonstrates system performance in various environmental conditions. The leader-follower algorithm is successfully deployed in an artificial cave environment simulating the confined and feature-poor conditions of a true cave. The system is tested in both fully lit and dark environments. VIO quality, localization drift, and recorded flight paths are examined to evaluate system stability and robustness in each scenario.

H.5 Balloon-Based High-Altitude Air Turbulence Measurement

Reed Spurling, Yong Xin Lai, Tayvien Williams, Jim Cronin, James Hamilton, Ryland Phipps, Sergey Shkarayev
(University of Arizona)

Air turbulence in Earth's atmosphere mixes gases, distributes heat, affects astronomical observations, and poses challenges to aircraft flight. The properties and effects of air turbulence in the upper atmosphere are insufficiently understood; thus, to improve our understanding of upper atmospheric turbulence, we—an undergraduate engineering senior design team working with the University of Arizona's Micro Air Vehicles Lab—are flying a turbulence-measuring sensor suite aboard a pair of high-altitude, scientific balloon missions. We will first launch a small latex weather balloon to 30 km altitude, carrying (1) a Pixhawk flight system with GPS, (2) a set of thermal anemometers, and (3) an ultrasonic anemometer to measure wind velocity and turbulence across a range of length scales at a data rate of 100 Hz. The next mission will occur aboard NASA's next High Altitude Student Platform (HASP) balloon flight this September. It will collect the same data at the same altitude but for a longer duration under a similar setup. We plan to share the preliminary results of our small latex weather balloon flight at this conference.

Poster Session

P.1 Evaluating Plant Growth in CubeSat Centrifuge Terrariums to Simulate Lunar Surface Conditions

Farah Alqaraghuli, Claire Pedersen, Jekan Thagavelautham
(SpaceTREx Laboratory, University of Arizona)

Establishing sustainable habitats on off-world bodies such as the Moon is critical for enabling the survival of astronauts for long term space missions. Central to this idea is the cultivation of plants on the lunar surface, serving a diverse range of purposes such as food production, carbon dioxide removal, and the overall enhancement of astronaut well-being to extend mission duration. Here, a concept is proposed to replicate lunar conditions in a centrifuge, growing various plant species to further examine the ability of plants to withstand space conditions. The proposed concept will be conducted inside a 4U terrarium that will be housed inside a 6U CubeSat in low Earth orbit (LEO). Each species of plant housed inside the terrarium will be subjected to conditions mirroring the lunar climate including similar microgravity, radiation exposure, sunlight access, temperature variations, humidity levels, and vacuum conditions. Each experiment will last a total of 28 Earth days, which is equivalent to one lunar day with alternating periods of daytime and nighttime simulating the variations in access to sunlight on the Moon. Temperatures ranging from 120 to -150 ℃ will be implemented to mimic day and night temperature fluctuations on the moon. Three plant species were chosen to undergo this experiment based on their resilience to survive harsh space conditions, their representation of a diverse range of species that will aid in the evaluation of the ability of plants to adapt to space conditions, and their relevance in addressing the various needs of astronauts in missions. Arabidopsis plants are small flowering plants with rapid growth rates and were selected because they are model organisms in plant biology and genetic studies making them ideal candidates for studying the life cycle of plants in space. Alfalfa seeds were chosen for their high nutritional value to astronauts, their resilience and ability to a wide range of environmental conditions, and their nitrogen fixing root system which presents an opportunity to be tested with lunar regolith. Douglas fir trees were chosen for their carbon sequestration and biomass production capabilities, hence making them suitable for constructing lunar structures and CO2 scrubbing if grown properly. This experiment will serve as a proof of concept for the beginning of cultivating life in extraterrestrial environments and will therefore present the possibility of extending mission duration and improving the quality of life for astronauts.

P.2 CubeSAT Centrifuge Terrarium

Jake Hathaway, Connor Zell, Hannah Perez, Neo Stilson, Paul Lynch
(SpaceTREx Laboratory, University of Arizona)

As the Svalbard Global Seed Vault faces imminent danger from glacial melting, Wildcat Engineers Dedicated to Guarding the Ecosystem through Space (WEDGES) have taken on the challenge of developing a solution. Sponsored by NASA and University of Arizona's Asteroids Laboratory, the team aims to demonstrate that organic life can be maintained and stored in a 3U CubeSAT. The CubeSAT utilizes artificial gravity via centrifuge, and an autonomous life support system to preserve the health of the plant. The prototype uses a BME 280 and Raspberry Pi 3A+ coupled with a water pump and IR lights to mitigate temperature losses from the dark side of the Earth. The CubeSAT will be considered a success if the contained organism can live for two weeks isolated with only the life support package. Parameters such as pressure, temperature, and humidity will be monitored and evaluated. Sensor data will be sent to a server which then can be queried from a computer. Several trials will be run to ensure the heating actuation is capable of desired heat addition. The water pump is used in tandem with the humidity sensor to ensure proper habitat for the organism. When presenting WEDGES's prototype, a two weeks long data history of different temperature, humidity, and pressure cycles can be observed. Alongside the data, the CubeSAT will demonstrate deployment of the scissor lift under centrifugal force.

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