Lunar Surface Innovation Consortium (LSIC)

Spring Meeting Program

May 04–05, 2022

Johns Hopkins Applied Physics Laboratory

Technical Organizing Committee

Jodi Berdis, JHU Applied Research Laboratory
Alice Cocoros, JHU Applied Research Laboratory
Milena Graziano, JHU Applied Research Laboratory
Karl Hibbitts, JHU Applied Research Laboratory
Kevin Hubbard, Arizona State University
Claudia Knez, JHU Applied Research Laboratory
Justin Likar, JHU Applied Research Laboratory
Bob Moses, NASA
Michael Nord, JHU Applied Research Laboratory
Jorge Núñez, JHU Applied Research Laboratory
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Kirby Runyon, JHU Applied Research Laboratory
Samalis Santini De Leon, JHU Applied Research Laboratory
Stacy Teng, JHU Applied Research Laboratory
Maneesh Verma, Stellar Space Industries
Juno Woods, Translunar LLC
Sean Young, JHU Applied Research Laboratory

LSIC Summary

The purpose of the Lunar Surface Innovation Consortium (LSIC) is to harness the creativity, energy, and resources of the nation to help NASA keep the United States at the forefront of lunar exploration.

LSIC operates in collaboration with the NASA Space Technology Mission Directorate under the Lunar Surface Innovation Initiative. LSIC fosters communications and collaborations among academia, industry, and Government. Members have expertise in LSII key capability areas.

Please visit the LSIC website for further information: http://lsic.jhuapl.edu

Agenda
Day 1 – Wednesday, May 4, 2022 (All times EDT)

9:30 AM	Coffee & Networking in Person and in GatherTown	
10:30 AM	In-Person Welcome and Logistics	**Dr. Rachel Klima,** LSIC Director, Johns Hopkins Applied Physics Laboratory (APL)
10:35 AM	Welcome & Intro to APL	**Dr. Jason Kalirai,** Mission Area Executive, Civil Space, APL **Dr. Robert Braun,** Sector Head, Space Exploration, APL
11:00 AM	Keynote Address	**Robert Cabana,** Associate Administrator, NASA
11:30 AM	NASA Space Tech Update	**Jim Reuter,** Associate Administrator for Space Technology, NASA
11:50 AM	**Break**	
12:00 PM	LSIC Update	**Dr. Rachel Klima,** LSIC Director, APL
12:15 PM	Panel: Law and Tech – Policy for the Moon	**MODERATORS:** **Aparna Srinivasan**, J.D., APL and **Dr. Angela Dapremont**, APL **PANELISTS:** **Dr. Timiebi Aganaba,** Senior Global Futures Scientist/Assistant Professor, Arizona State University **Chris Johnson,** Space Law Advisor, Secure World Foundation **Mary Guenther,** Director of Space Policy, Commercial Spaceflight Federation **Brian Stanford,** Senior Contracts Attorney, Office of the General Counsel, NASA **Jessy Kate Schingler,** Director of Policy and Governance, Open Lunar Foundation
1:15 PM	**Lunch Break**	
2:15 PM	Panel: Executive Committee	**MODERATORS:** **Dr. Rachel Klima,** LSIC Director, Johns Hopkins Applied Physics Laboratory (APL) **PANELISTS:** **Jessy Kate Schingler,** Open Lunar Foundation **Dr. Ariel Ekblaw,** MIT Space Exploration Initiative **Dr. George Sowers,** Colorado School of Mines **Dr. Michael Miller,** Southwest Research Institute **Dr. Ryan Watkins,** NASA SMD
3:00 PM	Panel: Modular Open Systems Approach: MOSA	**MODERATORS:** **Jessy Kate Schingler,** Open Lunar Foundation and **Dr. James Mastandrea**, APL **PANELISTS:** **Mark Mazzara,** Robotics Interoperability, Engineer & Project Manager, US Army **Meera Day Towler,** Senior Research Engineer, Southwest Research Institute **Matt DeMinico,** Power Portfolio Manager, NASA Glenn Research Center **Amalaye Oyake,** Senior Flight Software Engineer, Blue Origin **Chad Thrasher,** Systems Interoperability Lead, NASA's Artemis Campaign Development Division
4:00 PM	**Break**	
4:10 PM	Lightning Talks	
5:00 PM	Poster Session and Networking	
6:00 PM	**Adjourn**	

Agenda
Day 2 – Thursday, May 5, 2022 (All times EDT)

9:30 AM	Coffee & Networking in Person and in GatherTown	
10:30 AM	Welcome and Introduction	**Niki Werkheiser,** Director, Technology Maturation, NASA
10:40 AM	High Level Envisioned Future	**Walter Engelund,** Deputy Associate Administrator for Programs, NASA Space Technology Mission Directorate
11:00 AM	Envisioned Future: Power	**John Scott,** Principal Technologist for Power and Energy Storage, NASA
11:20 AM	Envisioned Future: ISRU	**Dr. Julie Kleinhenz,** Deputy for ISRU System Capability Leadership Team, NASA
11:40 AM	**Break**	
11:50 AM	Envisioned Future: Thermal	**Angela Krenn,** Principal Technologist, Thermal, NASA
12:10 PM	Envisioned Future: Excavation, Construction & Outfitting	**Dr. Mark Hilburger,** Principal Technologist for Structures, Materials, and Nano-technology, NASA
12:30 PM	Panel Discussions: Envisioned Future Q&A	**All previous NASA speakers**
12:50 PM	**Lunch Break**	
1:50 PM	LSIC Focus Group Reports	**APL Focus Group Facilitators:** Excavation and Construction, **Dr. Athonu Chatterjee** In Situ Resource Utilization (ISRU), **Dr. Karl Hibbitts** Extreme Access, **Dr. Angela Stickle** Extreme Environments, **Dr. Jamie Porter** Dust Mitigation, **Dr. Jorge Nunez** Surface Power, **Dr. Wesley Fuhrman**
2:50 PM	NASA I-Corps	**Maggie Yancey,** Lead for Entrepreneurship Development, NASA
3:00 PM	LuSTR Opportunities	**Dr. Harri Vanhala,** Space Technology Research Grants, NASA
3:10 PM	Value Network Update	**Dr. Kirby Runyon,** APL and **Jibu Abraham,** APL
3:20 PM	**Break**	
3:30 PM	Breakout Sessions	**TOPICS:** **Regolith to Rebar: Next Steps** **Funding Opportunities: LuSTR and More** **Envisioned Futures: Initial Feedback Discussions** **Space Law, MOSA, and the Big-Picture**
4:30 PM	**Break**	**Transition to plenary**
4:40 PM	Plenary Wrap-Up: Initial Findings and Recommendations	**Dr. Rachel Klima,** LSIC Director, APL
5:00 PM	**Adjourn**	

Speakers

Jibu Abraham

Senior Mechanical Engineer, JHU Applied Physics Laboratory

Jibu Abraham is a member of the Senior Staff in the Air & Missile Defense sector of APL. Jibu has served as Principal Investigator on multiple projects, with an emphasis in the development and fabrication of complex flight related hardware. He has designed, developed and analyzed mechanical/electromechanical components for missile systems, unmanned autonomous vehicles, and novel defense concepts for the Navy. Jibu has a bachelors and masters in mechanical engineering. Fun Note: Neil Armstrong left for the moon on Jibu's birthday (July 16th), long before he was born.

Dr. Timiebi Aganaba

Senior Global Futures Scientist/Assistant Professor, Arizona State University

Timiebi Aganaba is an assistant professor of Space and Society, in the School for the Future of Innovation in Society, an affiliate faculty with the Interplanetary Initiative, a senior global futures scientist with the Global Futures Lab, and holds a courtesy appointment at the Sandra Day O'Connor College of Law, all at Arizona State University. Timiebi was a post-doctoral fellow and is a senior fellow at the Centre for International Governance Innovation (CIGI)based in Waterloo, Ontario Canada where she focused on environmental and space governance. She is currently on the Advisory Board for the Space Generation Advisory Council supporting the UN Programme on Space Applications. She is also on the Science Advisory Board of World View Enterprises and the SETI Institute.

Timiebi has represented Nigeria at the UN as a Next Generation Aviation Professional at the International Civil Aviation Organization Model Council in Montreal (2014) and at the Legal subcommittee of the Committee on the Peaceful Uses of Outer Space in Vienna (2011). In 2017, Timiebi was the recipient of a Space Leaders Award from the International Astronautical Federation (IAF) and her doctorate received the George and Ann Robinson Award for advanced research capabilities. An avid and passionate communicator, Timiebi has been featured in the Washington Post, New York Times, CNN, NPR, LA Times, the Telegraph and Business Insider amongst others! She hosted and produced the 12 episode Ladies do Launch podcast and has acted as an international moderator for high level events such as the Dubai Expo 2020.

Speakers

Dr. Robert Braun

Sector Head, Space Exploration, JHU Applied Physics Laboratory

Dr. Robert D. Braun has more than 35 years experience as a space systems engineer, technologist, and organizational leader. He has contributed to the formulation, development, and operation of multiple space flight missions and is a recognized authority in the development of entry, descent and landing systems.

Dr. Braun serves on the executive leadership team of the Johns Hopkins Applied Physics Laboratory as Head of the Space Exploration Sector. He previously served as Director for Planetary Science at the Jet Propulsion Laboratory (2020-2022), Dean of the College of Engineering and Applied Science at the University of Colorado Boulder (2017-2020), a faculty member of the Georgia Institute of Technology (2003-2016) and a member of the technical staff of the NASA Langley Research Center (1989-2003).

In 2010-2011, Dr. Braun served as the first NASA Chief Technologist in more than a decade. In this capacity, he was responsible for development of the Agency's technology and innovation policy and programs. He created and led the initial implementation of a spectrum of NASA technology programs designed to build the capabilities required for our nation's future space missions. This activity spanned all ten NASA Centers, industry and academia, and fostered partnerships between NASA and other government agencies.

Dr. Braun is a member of the National Academy of Engineering, a Fellow of the AIAA and AAS, and the author or co-author of over 300 technical publications.

Ben Bussey

Lunar Surface Innovation Initiative Lead,
Principal Professional Staff, JHU Applied Physics Laboratory

Dr. Bussey is a planetary scientist who is currently the lead of the APL team supporting NASA's Space Tech's Lunar Surface Innovation Initiative. He earned a BA in Physics from Oxford University and a Ph.D. in Planetary Geology at University College London before moving to the United States. He gained both science and mission experience while working at the Lunar and Planetary Institute in Houston, the European Space Agency, Northwestern University and the University of Hawaii, before joining the Johns Hopkins University Applied Physics Laboratory. Bussey's research concentrates on the remote sensing of the surfaces of planets, particularly the Moon. He has a specific interest in the lunar poles, producing the first quantitative illumination maps of the polar regions. He co-authored the Clementine Atlas of the Moon, the first atlas to map both the lunar near side and far side in a systematic manner.

Dr. Bussey recently completed a 5-year assignment at NASA HQ which included being the Acting Deputy Associate Administrator of Exploration in NASA's Science Mission Directorate. Before that he was the Chief Exploration Scientist in NASA's Human Exploration and Operations Mission Directorate. Prior to his positions at NASA headquarters he was Principal Investigator of the NASA VORTICES SSERVI team and before that of a NASA Lunar Science Institute team that considered the exploration and scientific potential of the lunar poles. He was the Principal Investigator of the Mini-RF radar instrument on NASA's Lunar Reconnaissance Orbiter, and Deputy Principal Investigator of the Mini-RF radar instrument on India's Chandrayaan-1 mission. These instruments acquired the first radar data of the lunar poles and farside.

He enjoys planetary analog field work and has been fortunate to have twice been part of the Antarctic Search for Meteorites expedition to recover meteorites from the Antarctic glaciers.

Speakers

Robert Cabana

Associate Administrator, NASA

Robert D. Cabana is a former NASA astronaut, serving the agency's associate administrator, its third highest-ranking executive and highest-ranking civil servant. Previously Cabana was director of NASA's John F. Kennedy Space Center in Florida, managing all NASA facilities and activities at the spaceport.

Born in Minneapolis, Minnesota, Cabana graduated from the U. S. Naval Academy in 1971 with a bachelor's degree in mathematics. He became a naval aviator and graduated with distinction from the U.S. Naval Test Pilot School in 1981. In his career, Cabana logged over 7,000 hours in 50 different kinds of aircraft. He retired as a colonel from the Marine Corps in September 2000.

Cabana was selected as an astronaut candidate in June 1985 and completed training in July 1986. A veteran of four spaceflights, Cabana logged 38 days in space as the pilot on STS-41 and

STS-53 and mission commander on STS-65 and STS-88, the first assembly mission of the International Space Station.

Cabana is served in senior management positions at Johnson Space Center in Houston, ultimately becoming deputy director. He was named director of NASA's John C. Stennis Space Center in Mississippi in October 2007 and a year later was reassigned as the Kennedy director.

Dr. Josh Cahill

Deputy Director, LSIC

Senior Staff Scientist, JHU Applied Physics Laboratory

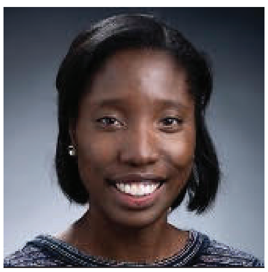
Dr. Joshua Cahill is the Deputy Director of the Lunar Surface Innovation Consortium (LSIC) and a Senior Staff Scientist in the Planetary Exploration Group at the Johns Hopkins Applied Physics Laboratory. He is a multi-disciplinary planetary geologist with experience in the fields of lunar and terrestrial spectroscopy and radar remote sensing, geochemistry, and petrology. He is a Co-Investigator on NASA's Lunar Reconnaissance Orbiter (LRO) mission supporting both the Mini-RF synthetic aperture radar and the Lyman Alpha Mapping Project (LAMP) instrument payloads. He has supported various aspects of these instrument's investigations of the lunar surface over the last 10 years. This includes utilizing Mini-RF observations to create some of the first global mapping perspectives of the Moon in S-band radar. His LRO research has focused upon characterization of the lunar surface and subsurface physical and thermophysical properties, composition, volatiles, how space weathering influences those interpretations, and polar and non-polar permanently shadowed regions. Dr. Cahill is also a Co-Investigator on the recently selected Lunar Vertex (LVx) mission which will investigate the legendary magnetic anomaly and lunar swirl, Reiner Gamma.

Speakers

Dr. Athonu Chatterjee

Excavation & Construction Focus Area Lead, LSIC
Senior Professional Staff, JHU Applied Physics Laboratory

Dr. Athonu Chatterjee is a researcher in the space exploration sector of APL. His background is in mechanical engineering, materials processing, and modeling and simulation. His present activities at APL include laser-material interaction, spacecraft design,and lunar exploration. Prior to joining APL, he worked at the research centers of General Electric (GE) and Corning. There he worked on new product and process development for diverse applications such as high-temperature ceramics matric composites (CMC) for aircraft engines, turbine blade manufacturing processes, solid-oxide fuel cells (SOFC), micro-reactors, etc. He obtained his Ph.D. in mechanical engineering from Stony Brook University, NY.



Dr. Angela Dapremont

Policy, Strategy, and Recruitment Lead, LSIC
Associate Staff, JHU Applied Physics Laboratory

Dr. Angela Dapremont is a Post Doctoral Fellow at the Johns Hopkins University Applied Physics Laboratory. As a member of the Lab's Planetary Exploration Group, Dr. Dapremont provides policy, strategy, and recruitment support to the Lunar Surface Innovation Consortium. Dr. Dapremont's scientific research is focused on understanding the composition of terrestrial bodies in the solar system. Her research publications have incorporated datasets from numerous orbital remote sensing missions including the Compact Reconnaissance Imaging Spectrometer for Mars (CRISM), the Context Camera (CTX), and the High Resolution Imaging Science Experiment (HiRISE) camera currently orbiting Mars. Dr. Dapremont also uses Moon Mineralogy Mapper (M3) data to investigate lunar surface composition and is an Affiliate of the Lunar Trailblazer mission.

Meera Day Towler

Senior Research Engineer, Southwest Research Institute

Meera Day Towler, P.E., is a Senior Research Engineer in Manufacturing and Robotic Technologies at Southwest Research Institute. She currently leads an initiative to transition advanced industrial robotics capabilities to meet the current and future needs of the space industry, both in orbit and on the ground. With a background in controls engineering, she has worked on numerous technical research and development projects across robotics and turbomachinery.

Speakers

Matt DeMinico

Power Portfolio Manager, NASA Glenn Research Center

Mr. DeMinico is the Power Portfolio Manager for NASA Glenn's GCD power projects. In that role he serves as the project manager for multiple projects including Regenerative Fuel Cell (RFC), Micro-grid definition and Interface converter for Planetary Surfaces (MIPS), Photovoltaic Investigation on the Lunar Surface (PILS), and 11 other projects. He led NASA's efforts with Lunar Surface Innovation Consortium (LSIC) to establish the LSIC Modularity and Standards working group. He previously served as the PM for the eMMRTG project.

Prior to joining NASA, he served as the U.S. Army's Deputy Chief Scientist for Robotics, where he guided formulation of the first two autonomy programs established under the Army's Modernization Strategy, re-prioritized the efforts of Army partner organizations to support Army Modernization, established the Modular Autonomy and Robotic Software (MARS) program, and led the interagency Robot Operating System – Military (ROS-M) program. He was also awarded a patent for a cyber-secure electro-mechanical interlock which is mathematically verifiable to prevent unauthorized remote triggering of safety-critical and cyber-vulnerable systems. He holds a Bachelor of Science in Computer Science degree from Kettering University.

Ariel Ekblaw

Executive Committee Member, LSIC
Director, MIT Space Exploration Initiative

Ariel Ekblaw is the founder and Director of the MIT Space Exploration Initiative, a team of over 50 graduate students, staff, and faculty actively prototyping the artifacts of our sci-fi space future. Founded in 2016, the Initiative now includes a portfolio of 40+ research projects focused on life in space (from astrobiology to space habitats), and supports an accelerator-like R&D program that enables a broad range of payload development. For the Initiative, Dr. Ekblaw drives space-related research across science, engineering, art, and design, and charters an annually recurring cadence of parabolic flights, sub-orbital, and orbital launch opportunities. Dr. Ekblaw forges collaborations on this work with MIT departments and space industry partners, while mentoring Initiative research projects and providing technical advice for all mission deployments. The Initiative is preparing for its first lunar payload, as part of an MIT-wide effort, in 2024. Dr. Ekblaw brings a humanist approach to her research at MIT, with undergraduate degrees in Physics, and Mathematics and Philosophy from Yale University, a Master's in distributed systems from the MIT Media Lab, and her recent MIT PhD in self-assembling space structures for space architecture, via the TESSERAE platform.

Speakers

Walter Engelund

Deputy Associate Administrator for Programs, NASA Space Technology Mission Directorate

Walter (Walt) C. Engelund began serving as the Deputy Associate Administrator for Programs in the Space Technology Mission Directorate (STMD) at NASA Headquarters in September of 2019, and provides executive leadership and management of the full range of space technology programs within STMD, with an annual investment value of nearly $1Billion. He is responsible for budget planning and allocation of resources, and serves as the decisional authority for project and program content, ensuring that technology investments align with the NASA Strategic Plan and Roadmaps.

Prior to his appointment with STMD, Engelund spent 30 years at NASA's Langley Research Center in Hampton, VA, most recently as the Director of the Space Technology and Exploration Directorate, where he led an organization that was responsible for developing technologies for human spaceflight and robotic exploration, including support for the development of the Space Launch System (SLS), the Orion Launch Abort System, Mars Entry, Descent, and Landing Instrumentation (MEDLI), commercial launch vehicles, and multiple other technologies to enable future human and robotic space exploration missions.

He also previously served as the Chief Engineer at NASA's Langley Research Center, and was responsible for technical oversight for Langley's diverse research and development portfolio, spanning aeronautics, human and robotic space technologies, and Earth science and remote sensing systems.

He is a recognized expert, reviewer, and consultant for hypersonic flight and planetary entry systems for NASA and other government agencies. He has authored or co-authored over 60 conference and peer reviewed archival/journal publications. He is an Associate Fellow in the American Institute of Aeronautics and Astronautics, and a lifetime member of Tau Beta Pi, the National Engineering Honor Society, and is the recipient of numerous NASA Achievement Awards including NASA's Exceptional Engineering Achievement Medal and the Exceptional Achievement Medal.

Dr. Wesley Fuhrman

Surface Power Focus Area Lead, LSIC
Senior Professional Staff, JHU Applied Physics Laboratory

Dr. Wesley Fuhrman is a condensed matter physicist passionate about the interface between public and private science, with active research in remote sensing and advanced materials. Wesley earned his PhD from The Johns Hopkins University in spectroscopy of correlated topological materials, involving techniques such as elastic and inelastic neutron scattering, neutron spin echo, prompt-gamma activation analysis, X-ray absorption spectroscopy, X-ray magnetic circular dichroism, etc. Following this, he was an inaugural Schmidt Science Fellow, a program in partnership with the Rhodes Trust which builds interdisciplinary skills that cross boundaries between academia, industry, and government. Materials expertise spans solid-state synthesis (including uranium compounds), characterization, spectroscopy, and theory of strongly correlated and topological materials.

Speakers

Mary Guenther

Director of Space Policy, Commercial Spaceflight Federation

Mary Guenther is the Director of Space Policy for the Commercial Spaceflight Federation (CSF). CSF is the leading national trade association for the commercial space industry, with roughly 90 member companies and organizations across the United States. CSF is focused on laying the foundation for a sustainable space economy and democratizing access to space for scientists, students, civilians, and businesses.

At CSF, Guenther leads the policy development and lobbying efforts, where she is focused on promoting policies that enable fair and open competition, spur innovation, and expand public-private partnerships.

Before joining CSF, Guenther served as a Professional Staff Member at the Senate Commerce Committee. In that position, she was responsible for developing and moving space, manufacturing, and science legislation through the Congress as well as performing oversight on NASA, NSF, NIST, FAA AST, and the DOC Office of Space Commerce. She was integral to the Senate passage of the United States Innovation and Competition Act, which incorporated the NASA Authorization Act of 2019.

Dr. Karl Hibbitts

In Situ Resource Utilization (ISRU) Focus Area Lead, LSIC
Principal Staff Scientist, JHU Applied Physics Laboratory

As a planetary scientist, Dr. Karl Hibbitts conducts research to understand the compositions of the surfaces of airless bodies in our Solar System, including how otherwise volatile materials like water can exist on the illuminated Moon. He is deputy-PI of the Europa Clipper MISE infrared mapping spectrometer and was deputy-PI and mid-IR camera lead on the NASA BRRISON and BOPPS stratospheric balloon missions that demonstrated the scientific and cost effectiveness of spectral imaging of solar system objects from NASA balloon platforms in the upper stratosphere. Dr. Hibbitts also leads an active planetary laboratory spectroscopy effort in a facility he developed at APL that couples VUV –LWIR spectral capabilities with a UHV system capable of mimicking the vacuum, temperature, and radiation environments of the Moon and other airless bodies in our solar system.

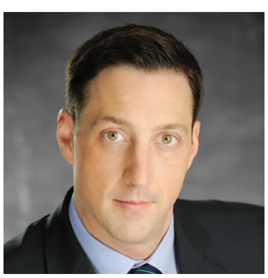
Speakers

Dr. Mark Hilburger

Principal Technologist for Structures, Materials, and Nanotechnology, NASA

Dr. Mark Hilburger is a Senior Research Engineer in the Space Technology Exploration Directorate at NASA Langley Research Center in Hampton VA. He was recently appointed Space Technology Mission Directorate (STMD) Principal Technologist (PT) for Structures, Materials, and Nanotechnology at NASA. His roles and responsibilities include developing technology investment plans across his assigned areas in coordination with NASA Exploration Programs; identify technology needs that will enable exploration; lead focused technology studies and coordinate with Agency Capability Managers in technology development activities to maintain and advance capabilities. Previous to his STMD PT appointment, he was the Principal Investigator and Manager of the NASA Engineering and Safety Center's Shell Buckling Knockdown Factor Project from 2007 to 2018. The goal of the project was to develop and validate new design, analysis, and testing methods for buckling-critical launch vehicle structures. His responsibilities included defining and managing the integration of analysis, design, manufacturing, and test teams to develop an efficient, multi-disciplinary approach to optimal structural design, verification, and validation. His staff included experts across three NASA centers, industry, and academia. He also coordinated Space Act Agreements with Boeing, Northrop-Grumman, the German Research Laboratory (DLR), and the European Space Agency (ESA).

Dr. Mark Hilburger specializes in High-Fidelity Analysis and Design Technology Development and Experimental Methods for Aerospace Structures. He has been presented with numerous awards and including the 2018 Middle Career Stellar Award presented by The Rotary National Award for Space Achievement; the NASA Exceptional Engineering Achievement Medal, 2010; the NASA Engineering and Safety Center Engineering Excellence Award, 2009; selected as of the nation's top 100 young engineers and scientist by the National Academy of Engineering, 2009; and the NASA Silver Snoopy Award, (Astronauts' Personal Achievement Award), 2006. He received his Ph.D. and Master of Science in Aerospace Engineering from the University of Michigan in Ann Arbor, MI in 1998 and 1995, respectively, and his Bachelor of Science in Mechanical Engineering from Rutgers University in New Brunswick, NJ in 1993.



Chris Johnson

Space Law Advisor, Secure World Foundation

Christopher Johnson is the Space Law Advisor at the Secure World Foundation, and a Professor of Law (Adjunct) at the Georgetown University Law Center where he co-teaches the Space Law Seminar. He is also a Faculty Member at the International Space University and a Member of the International Institute of Space Law. Mr. Johnson is also a Core Expert and Rule Drafter in the MILAMOS project, a Field Editor at the Journal of Space Safety Engineering, on the Board of Editors of the journal Air and Space Law, and on the Academic Review Board of the Cambridge International Law Journal. Mr. Johnson has written widely on space law and policy issues, and represents the Secure World Foundation at the United Nations Committee on the Peaceful Uses of Outer Space (COPUOS).

Speakers

Dr. Jason Kalirai

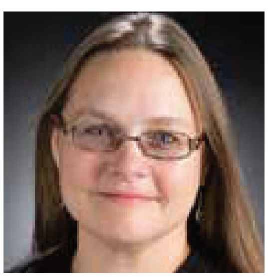
Mission Area Executive, Civil Space,
JHU Applied Physics Laboratory

Dr. Jason Kalirai is the Mission Area Executive for Civil Space in the Space Exploration Sector of the Johns Hopkins Applied Physics Laboratory (APL). He joined APL in November 2018 and is leading the implementation of innovative and cost-effective solutions to critical civil space challenges by developing space science missions, instruments, and research programs. Major Civil Space programs under development and operation at APL include New Horizons, Parker Solar Probe, DART, Europa Clipper, Lunar Vertex, IMAP, EZIE, Dragonfly, and more. Dr. Kalirai also leads a wide range of APL engagements efforts in the space industry. Prior to joining APL, Dr. Kalirai served as the multi-mission project scientist at NASA's Space Telescope Science Institute. He has published over 100 research papers on topics related to stellar and galactic evolution and was won numerous awards for his achievements. Dr. Kalirai earned his Bachelors, Masters, and PhD in astrophysics from the University of British Columbia. He completed a postdoctoral fellowship as a Hubble Fellow at the University of California at Santa Cruz.

Dr. Julie Kleinhenz

Deputy for ISRU System Capability Leadership Team, NASA

Dr. Julie Kleinhenz is the deputy lead for the NASA's ISRU System Capability Leadership Team, which coordinates ISRU strategy across NASA. She has been working ISRU since 2006, with a primary focus on developing methods of extracting water and oxygen from lunar and Martian regolith. She helped developed one of the largest dirty thermal vacuum chambers at NASA and lead test campaigns in the facility for 10 years. She has led and participated in numerous study teams focused on lunar and Mars ISRU architecture, system modeling, and ISRU measurement needs. Dr. Kleinhenz is currently working as integration system engineer for the PRIME-1 mission, is a Co-I on the VIPER mission science team, and is a member of the NASA simulant advisory group.



Dr. Rachel Klima

Director, LSIC
Principal Staff Scientist, JHU Applied Physics Laboratory

Dr. Rachel Klima is the Director of the Lunar Surface Innovation Consortium and a principal staff scientist in the Planetary Exploration Group at the Johns Hopkins Applied Physics Laboratory. Dr. Klima's research focuses on integrating laboratory analysis of lunar, meteoritic, synthetic, and terrestrial rocks and minerals with near through mid-infrared spectral measurements of solid bodies in the solar system to understand such topics as the thermal/magmatic evolution of the Moon, distribution of minerals, water, and hydroxyl on the lunar surface, and the composition of Mercury's crust. Dr. Klima has been involved with numerous missions to bodies throughout the solar system, including the Dawn Mission, the Moon Mineralogy Mapper, a hyperspectral imaging spectrometer flown on Chandrayaan-1, MESSENGER, and Europa Clipper. She previously served as the Deputy PI of the Volatiles, Regolith and Thermal Investigations

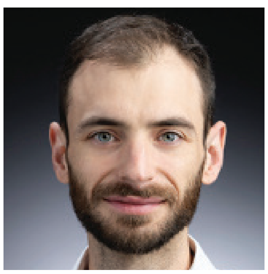
Consortium for Exploration and Science (VORTICES) team for the NASA Solar System Exploration Research Virtual Institute (SSERVI). She currently serves as the Deputy PI of the Lunar Trailblazer Mission and is a participating scientist on the Korea Pathfinder Lunar Orbiter.

Speakers

Angela Krenn

Principal Technologist, Thermal, NASA

Angela Krenn began working at NASA's Kennedy Space Center in 2002 and supported 25 Space Shuttle missions as an operator of the liquid hydrogen propellant systems. Mrs. Krenn also has experience with design and analysis for cryogenic ground systems as well as research and technology developments supporting cryogenic fluid management in ground, space, and surface applications. She has experience with strategy and planning for the lunar Human Landing System and as a member of the Mars Architecture Team. Mrs. Krenn currently serves as the Principal Technologist for thermal management systems in the agency's Space Technology Mission Directorate. In this role she develops strategies and technical content for initiating and executing projects related to active and passive thermal control systems with applicability to cryogenic fluid management, crew habitable volumes, in-space nuclear systems, extreme environments survival, and more.



Dr. James Mastandrea

MOSA Working Group Lead, LSIC
Senior Professional Staff, JHU Applied Physics Laboratory

Dr. James P. Mastandrea is a Senior Professional Staff member at the Johns Hopkins University Applied Physics Laboratory's Space Exploration Sector. He has aBS in Mechanical Engineering and Materials Science & Engineering, and a MS and PhD in Materials Science & Engineering all from the University of California,Berkeley. He has experience in computational materials science, material nucleation and growth, microstructural evolution of materials, and understanding material performance with an emphasis on semiconductors and metals. He serves as the LSIC Modular Open Systems Approach (MOSA) working group lead and is a facilitator for the Surface Power focus group. He also serves on the project management team of a NASA Heliophysics' study on an Interstellar Probe, a mission concept that would explore our habitable astrosphere and our local interstellar medium.

Mark Mazzara

Robotics Interoperability, Engineer & Project Manager, US Army

Mark Mazzara is the systems engineering & architecture lead for Project Manager (PM) Force Projection (FP), US Army Program Executive Office,Combat Support & Combat Service Support (PEO CS&CSS). Mark has previously performed a variety of systems engineering & PM positions in Army ground systems PEOs, including team leads for systems engineering & interoperability, Assistant Product Manager, Program Officer, Department of the Army Systems Coordinator (DASC) and PM chief engineer. Mark holds a BS in Mechanical Engineering and MS in Systems Engineering, both from Oakland University. Mark is Defense Acquisition University certified at Level III in both Systems Engineering and Program Management.

Speakers

Michael Miller

Executive Committee Member, LSIC
Institute Scientist, Southwest Research Institute

Dr. Michael Miller has over 36 years of experience as a physical and synthetic chemist, specializing in materials science, surface science, solid-state chemistry and physics, as well as molecular spectroscopy. The main thrust of his work has been on the development of first-principles theoretical models and experimental methods aimed at predicting or determining physical and chemical pathways for the formation or disposition of molecules and materials. He directs SwRI's Sorption Science Laboratory (S3L) - a research facility dedicated to investigating the gas sorption properties of natural and synthetic materials over a broad range of thermodynamic conditions. In the area of planetary studies, he has contributed to the needs of future lander missions that include the development of chemical processes for in situ propellant production (ISPP) on Mars, and led a team of scientist to develop an inverted surface enhanced Raman spectroscopy (iSERS) technique for biomarker detection. Most recently, he has been working on the experimental and theoretical determination of noble gas fractionation in Mars analogue systems, non-binary computing architectures based on photonic-molecular transduction, and modeling MW-IR and MW-Raman double resonance effects in molecular systems as the foundation for stand-off detection technologies.

Dr. Jorge Núñez

Dust Mitigation Focus Area Lead, LSIC
Senior Professional Staff, JHU Applied Physics Laboratory

Dr. Jorge Núñez is a senior planetary scientist and astrobiologist in the Space Exploration Sector at the Johns Hopkins University Applied Physics Laboratory. He received dual BS degrees in Mechanical Engineering and Physics from the University of Alabama at Birmingham (UAB) and Ph.D. in Geological Sciences from Arizona State University (ASU). His primary research focuses on studying the geology and composition of planetary surfaces from the micro-to the macro-scale using a variety of remote sensing and in situ techniques, as well as development of instruments and technologies for extreme environments such as the Moon, Mars, and beyond. He is a team member on multiple planetary missions and instruments, including the Mars 2020 and Dragonfly missions. He has expertise in microscopy, visible/near-infrared spectroscopy, and instrument development. Dr. Núñez also coordinates the Planetary Exploration Research Lab (PERL) at APL. Over the years, he has participated in several analog field tests simulating robotic and human missions to the Moon, including NASA ISRU and Desert RATS field tests, and worked with lunar samples collected during the Apollo missions. He is a Fulbright Scholar and the recipient of a NASA Early Career Fellowship and multiple NASA Group Achievement awards. Asteroid 176610 Núñez was named in his honor.

Speakers

Amalaye Oyake

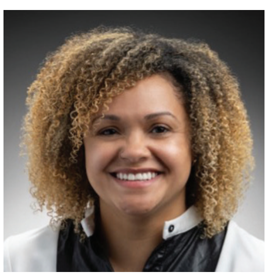
Senior Flight Software Engineer, Blue Origin

I am a Senior Flight Software Engineer at Blue Origin working in the areas of Space Robotics, Command and Data Handling Systems, and Avionics Flight Software. My work involves developing software for robotic systems in Low Earth Orbit. Prior to work at Blue Origin, I worked at the NASA Jet Propulsion Laboratory (JPL) on Space Internet concepts, also known as Disruption Tolerant Networking (DTN). This culminated in the first ever deep space Internet data transmission in 2008 using protocols developed at JPL with the assistance of Dr. Vint Cerf.

My experience has included work on the Earth Surface Mineral Dust Source Investigation (EMIT), an external payload on the International Space Station. I was previously working on Spacecraft Atmosphere Monitor (a mass spectrometer that is an ISS internal payload) and the Jason-3 Earth observing satellite. I have also been one of the principal organizers of the Workshop on Spacecraft Flight Software - This yearly workshop provided an opportunity to present concepts in flight software architectures, as well as the IEEE Conference on Space Mission Challenges in Information Technology (SMC-IT).

I have previously worked on other interesting space projects most notably Cassini, Mars Pathfinder, Mars Exploration Rover, and the Mars Science Laboratory as well as internal and external payloads on the International Space Station (ISS). My skills include embedded systems, flight software, ground systems, communication protocols, software frameworks and high-reliability avionic systems using Time-Triggered Ethernet, C++, C, Java, Perl, Python, PHP, Tcl/Tk, Lisp, Fortran, LabView, MATLAB, Linux, VxWorks, RTEMS, cFS, F-Prime, and ROS 2.

I am from the United States Virgin Islands, I grew up in Canada, Nigeria, the Bahamas and the U.S. Virgin Islands.



Dr. Jamie Porter

Extreme Environments Focus Area Lead, LSIC
Senior Professional Staff, JHU Applied Physics Laboratory

Dr. Jamie Porter is a radiation effects engineer at Johns Hopkins Applied Physics Laboratory. She earned a BS, MS, and Ph.D. in Nuclear Engineering from the University of Tennessee. At APL, she helps lead the radiation modeling and charging effects team and serves as an Assistant Group Supervisor for Space Environmental Effects. She currently serves as APL Radiation Lead of Europa Clipper and Dragonfly, missions to extreme but very different environments. She has a passion for driving innovation through diversity and enabling others to reach their goals.

James Reuter

Associate Administrator for Space Technology, NASA

James L. Reuter is the associate administrator for the Space Technology Mission Directorate (STMD) at NASA Headquarters in Washington. He provides executive leadership and management of the technology programs within STMD, with an annual investment value of more than $1 billion.

During his almost four-decade career at NASA, Mr. Reuter has held several leadership positions, including: STMD deputy associate administrator, senior executive for technical integration at NASA's Marshall Space Flight Center in Huntsville, Alabama, chair of the standing review board of the Exploration Systems Division at NASA Headquarters, deputy manager of the Space Shuttle Propulsion Office, and environmental control and life support manager for the International Space Station.

Mr. Reuter has received numerous NASA awards and honors, including a Presidential Rank Award, Distinguished Service Medal, Outstanding Leadership Medal, NASA Exceptional Achievement Medal, and NASA Exceptional Service Medal.

Dr. Kirby Runyon

Senior Staff Scientist, JHU Applied Physics Laboratory

Dr. Kirby Runyon co-facilitates the ISRU Focus Group within LSIC, and is a senior staff scientist at APL. Dr. Runyon is passionate about enabling a sustained human presence on and around the Moon. His research interests center around lunar and planetary geomorphology through studying images of planetary surfaces. Specifically, Dr. Runyon is interested in geologic mapping on the Moon to determine specific landing and/or exploration zones from which to collect age-dateable samples to inform the history of large lunar basin formation. He has recently become interested in the geology of Venus and has begun studying the processes of impact cratering there. Laboratory experiments into impact cratering and impact crater ejecta emplacement round out his research interests. Recently, he has flown as both a researcher and a weightlessness coach on reduced gravity parabolic flights and is interested in advocating for increased experimentation on such parabolic flights. Dr. Runyon is a science team member on the New Horizons mission to Pluto, Arrokoth, and the outer heliosphere and has been the planetary science lead or the project scientist for two mission concept studies: Interstellar Probe and Neptune Odyssey.

Speakers

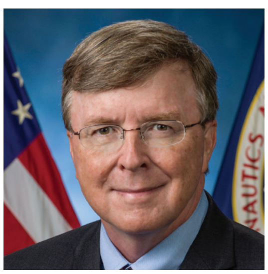
Jessy Kate Schingler

Executive Committee Member, LSIC
Director of Policy and Governance, Open Lunar Foundation

Jessy Kate Schingler is a founder and Director of Strategy at the Open Lunar Foundation. She is a recognized leader in lunar policy, a scholar of governance practices in environments of self-organization, and a regular convener and community organizer.

Ms. Schingler has helped to build capacity on lunar policy topics in both the domestic and international community, providing invited briefings on lunar policy and coordination to both NASA and the State Department, international government officials, and as Open Lunar's representative to the UN's Committee on the Peaceful Uses of Outer Space. Ms. Schingler has contributed to analyses on landing pads and dust mitigation, sustainability, salvage, payload determination, orbital use, cislunar security and resource utilization. She established Open Lunar's program applying sustainability science and political economy scholarship to natural resource systems on the Moon, looking at specific resource systems and questions of scarcity and contention. Currently Ms. Schingler is leading Open Lunar's strategic initiative related to lunar communication networks.

Jessy Kate is a main stage TED speaker, a PhD student at Paris 2 Panthéon-Assas University in France, and a research affiliate at Harvard's Berkman Klein Center for Internet and Society.



John Scott

Principal Technologist for Power and Energy Storage, NASA

John Scott currently serves as the Principal Technologist for Power and Energy Storage in the Space Technology Mission Directorate at NASA Headquarters. After beginning his aerospace career in propulsion at TRW Space & Technology (now a division of Northrup Grumman), Mr. Scott has served at NASA's Johnson Space Center for over thirty years in engineering, project management, and supervisory positions in support of the Space Shuttle, International Space Station, Orion, and various Human Exploration study programs. Immediately prior to his current posting, he served as Chief of the Energy Conversion Branch and as Chief Technologist in the Propulsion and Power Division at NASA-Johnson.

As Principal Technologist and a senior leader, John leads a nationwide team in advancing the power and energy storage technologies needed to accomplish NASA's goals for space exploration and to accelerate the growth of the commercial space industry.

Mr. Scott is a published author on spacecraft fuel cell and nuclear power systems. He holds a BS in Mechanical Engineering from Rice University and an MS in Mechanical Engineering and an MBA from UCLA.

Speakers

George Sowers

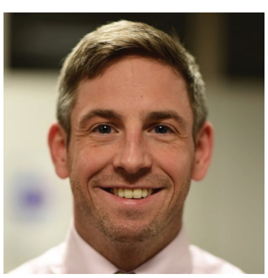
Executive Committee Member, LSIC
Professor, Space Resources, Colorado School of Mines

Dr. George Sowers has 30 years of experience in the space transportation field working for Martin Marietta, Lockheed Martin and the United Launch Alliance (ULA). In 2017, he retired from his position as Vice President and Chief Scientist at ULA where his team developed an architecture for fully reusable in-space stages fueled by propellant mined, refined and distributed in space. Dr. Sowers is now a professor at the Colorado School of Mines as part of the world's first and only graduate program in space resources. His current research interest is developing the ice resources of the Moon to fuel the cislunar economy. He holds a BS in Physics from Georgia Tech and a PhD in Physics from the University of Colorado. Dr. Sowers is a fellow of the American Institute of Aeronautics and Astronautics (AIAA).

Aparna Srinivasan, J.D.

Legal Analyst, JHU Applied Physics Laboratory

Ms. Aparna V. Srinivasan is a licensed attorney with degrees from Northwestern University and the University of Maryland School of Law. As a former federal attorney, she brings over a decade of experience in advising senior executives on regulatory matters, managing legal risk, and issuing legal memoranda detailing implications of certain actions based on existing regulatory code or case law. Additionally, Aparna has successfully litigated scores of individual and class action cases as lead federal counsel on behalf of the United States Government, to include the DoD. At the Johns Hopkins Applied Physics Laboratory, Aparna is a section supervisor in the Asymmetric Operations Sector and contributes to technical studies as a SME on topics that intersect with and ride the edges of technology and policy, particularly within the realm of space systems analysis and engineering.



Brian Stanford

Senior Attorney, Office of the General Counsel, NASA

Brian Stanford serves as a senior attorney-advisor at NASA Headquarters Office of the General Counsel in the Contracts and Acquisition Integrity practice group. Brian provides advice and counsel to agency senior leadership on the full spectrum of federal procurement and government contracting issues across the enterprise, and in particular, acquisition strategy for NASA/commercial space sector activities. Currently, Brian serves as directorate lead counsel to the Space Technology Mission Directorate. Brian began his career in private practice with the firm of Fried, Frank, Harris, Shriver & Jacobson in the government contracts practice group. There, he advised clients in defense, aerospace, national security, and support services lines of business.

Dr. Angela Stickle

Extreme Access Focus Area Lead, LSIC
Senior Research Scientist, JHU Applied Physics Laboratory

Dr. Angela Stickle is a planetary geologist with a background in Aerospace and Mechanical Engineering, magnetospheric physics, and impact processes on planetary surfaces. She received her bachelors degrees in Aeronautical/Astronautical Engineering as well as Earth and Space Sciences from the University of Washington, and her Masters' degrees in Geology and Engineering and Ph.D in Geological Sciences from Brown University. She is currently a senior research scientist at the JHU Applied Physics Laboratory. Her work focuses on impact processes in the solar system, including the Moon, Mars, asteroids, and the icy moons of Saturn and Jupiter. She is a Co-Investigator on the Mini-RF radar and LRO-LAMP instrument aboard the Lunar Reconnaissance Orbiter, the Dragonfly mission, and leads the impact modeling team for the Double Asteroid Redirection Test. Her research includes lunar surface evolution and maturation, experimental and numerical studies of damage formed by hypervelocity impacts, dynamic failure and fragmentation of materials, planetary defense, as well as cratering processes in icy targets. She uses an interdisciplinary approach to better understand impact phenomena, combining experiments (impact and dynamic failure) with numerical models and remote sensing to evaluate impact structures.

Chad Thrasher

Systems Interoperability Lead,
NASA's Artemis Campaign Development Division

Chad Thrasher currently lives in Huntsville, Alabama, working for NASA at Marshall Space Flight Center, where he serves as the Interoperability Lead for the NASA's Artemis Campaign Development Division, for the Systems Engineering and Integration (SE&I) organization. He leads efforts to ensure systems developed by multiple Artemis NASA programs (including Gateway, and Human Landing System), international partners, and commercial organizations, will be able to successfully interact with each other in either the lunar orbit or on the lunar surface.

Mr. Thrasher has supported NASA for over 25 years. Initially working as a NASA support contractor and then joining as a civil service employee in 2005, when he assisted in the manufacture and retrofitting of External Tanks for the Shuttle Program and on an In-Flight Anomaly Team, as a member of the Safety and Mission Assurance Office. In 2006, Mr. Thrasher returned to Marshall to serve as a lead safety engineer for the Ares I Vehicle Integration efforts. He has since supported the Commercial Crew Program, the Space Launch System Program, and served as a branch chief of the Systems Definition and Integration Branch. He has performed detail assignments to NASA Headquarters, the Jet Propulsion Laboratory, and Armstrong Flight Research Center. His career has focused on safety, aborts, and integration across multiple disciplines and programmatic boundaries.

Dr. Harri Vanhala

Space Technology Research Grants, NASA

Dr. Harri Vanhala is the Lead for the Lunar Surface Technology Research (LuSTR) program element at the Space Technology Research Grants Program at NASA's Space Technology Mission Directorate. The goal of LuSTR is to advance technologies for lunar surface exploration and to accelerate the technology readiness of key systems. Technologies developed under LuSTR support the Artemis program and align with the six focus areas of NASA's Lunar Surface Innovation Initiative. Dr. Vanhala has been involved with numerous NASA programs in the past, including Flight Opportunities, Fundamental Physics, the Physical Sciences Program, MESSENGER, and astrophysics research programs.

Ryan Watkins

Program Scientist, Exploration Science Strategy and Integration Office (ESSIO), NASA

Dr. Ryan Watkins is a Program Scientist in the Exploration Science Strategy and Integration Office (ESSIO) within SMD at NASA Headquarters. She is responsible for managing the overall science goals of multiple Commercial Lunar Payload Sciences (CLPS) deliveries and supports multiple lunar science and exploration initiatives under the Lunar Discovery and Exploration Program (LDEP). She currently serves as lead Program Scientist for the second Payloads and Research Investigations on the Surface of the Moon (PRISM) program. Prior to coming to NASA HQ, Dr. Watkins served as a Research Scientist, where she specialized in using photometry to understand physical and compositional properties of the lunar surface, and in integrating planetary data sets to assess landing site safety hazards for future missions. She has previously served on the Lunar Reconnaissance Orbiter Camera Science Team, the LEAG Executive Committee, the Organizing Committee for Next Generation Lunar Scientists and Engineers Group (NextGen), and Blue Origin's Science Advisory Board.

Niki Werkheiser

Director, Technology Maturation, NASA

Niki Werkheiser serves as the Director for Technology Maturation in the Space Technology Mission Directorate (STMD) at NASA Headquarters. The Technology Maturation portfolio includes over 120 projects within the Game Changing Development (GCD) Program and the Lunar Surface Innovation Initiative (LSII). In this role, she leads the advancement of key technologies for future space missions, including establishing policy, formulating budgets, and providing technical leadership. Prior to her current role, Ms. Werkheiser led the Agency's In-Space Manufacturing (ISM) efforts, including the development of novel, on-demand manufacturing, repair, and recycling capabilities.

She brings a wealth of expertise and a proven approach to managing complex projects and has over 25 years of experience developing and flying new technologies in space. Ms. Werkheiser is particularly passionate about creating competitive programs and partnerships across government, industry, academia, and non-profit organizations. Ms. Werkheiser holds a Master of Science Degree from the University of Alabama at Huntsville with an emphasis in Gravitational and Space Biology, as well as a Bachelor of Science in Biology and a Bachelor of Arts in Russian Language and Studies.

Maggie Yancey

Lead for Entrepreneurship Development, NASA

Maggie Yancey is on a Federal Detail at NASA as the Entrepreneur Development Lead for NASA's Science Mission Directorate and the Space Technology Mission Directorate (STMD), she is currently working to advance commercialization opportunities for current and future NASA entrepreneurs in academia. Her home agency is at the U.S. Department of Energy in the Wind Energy Technologies Office and has been leading the Community Impacts Research and Outreach portfolio working on important climate change challenges connecting small businesses, entrepreneurs, and communities to wind energy innovation opportunities to provide clean, reliable, and low-cost power on both land and water for the U.S. She started her Federal career as a 2015 Presidential Management Fellow. She is a graduate of University of Nebraska with a Master of Public Administration and a Bachelor of Journalism from the University of Texas at Austin.

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Flexible DC-Energy Router based on Energy Storage & Integrated Circuit Breaker. Nihanth Adina[1] and Jin Wang[2], [1,2]Department of Electrical and Computer Engineering, The Ohio State University, [1]adina.1@osu.edu, [2]wang.1248@osu.edu, (Contact: adina.1@osu.edu)

Introduction: The recent advancements in control of dc microgrids, solid state circuit breakers and Wide Band Gap (WBG) power device based high power density power converters can benefit and have a huge impact on the lunar based power systems.

Development Objectives: The goal is to combine the Smart Resistor [1] [2] concept, which is a wide bandwidth controller enabled by WBG devices and energy storage systems, and the T-Breaker [3], which is a modular and scalable dc circuit breaker, to realize a flexible DC-Energy Router (Figure 1) between and within a wide range of lunar microgrids (Figure 2).

A 120 V 10 kW GaN based high power density prototype would be built and a digital twin platform will be utilized to validate the DC-Energy Router functionalities:

- Power quality improvement
- Transient stability improvement
- Fault protection
- Real time power flow

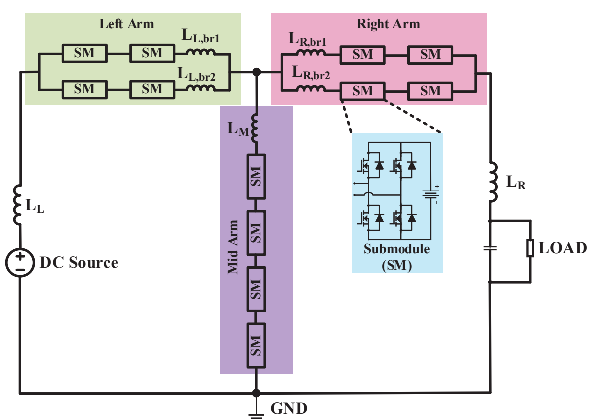

Figure 1: Illustration of the concept of the DC-Energy Router in a single-source single-load system.

Approach:

- Modular design of the dc-energy router
- Co-optimization of system architecture and layered control strategies
- Flexible energy flow control and stability improvement by coordinating Droop lines of energy sources and Smart Resistor lines of loads
- Fault current limiting, fast breaking and system re-configuration with integrated energy storage devices
- Digital twin and prototype-based validation

Impact & Infusion:

- Modular and flexible solution for control, protection and interoperability
- Fuel saving and reliability improvement
- Reduction in fault energy and collateral damage
- The planned digital twin, the high-power density prototype and hardware platform will enable many future research

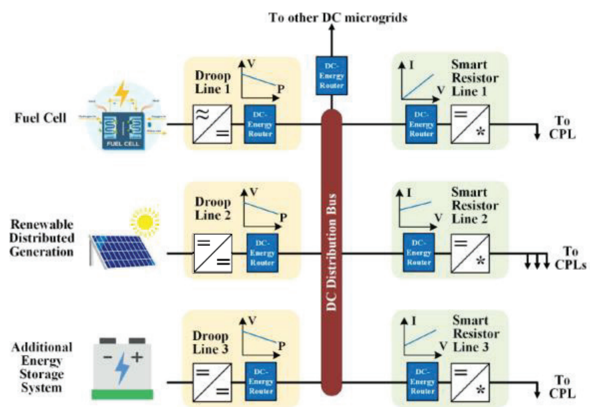

Figure 2: Installations of DC-Energy Routers at different locations of a conceptual lunar power system.

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[1] E. Bauer et al. (2017) "Smart resistor: Trajectory control of constant power loads in DC microgrids," *2017 IEEE Energy Conversion Congress and Exposition (ECCE)*, pp. 4832-4838. [2] K. A. Potty et al. (2020), "Smart Resistor: Stabilization of DC Microgrids Containing Constant Power Loads Using High-Bandwidth Power Converters and Energy Storage," in *IEEE Transactions on Power Electronics*, vol. 35, no. 1, pp. 957-967, Jan. 2020. [3] Y. Zhang et al. (2021) "T-Type Modular Dc Circuit Breaker (T-Breaker) for Future Dc Networks," *2021 IEEE Applied Power Electronics Conference and Exposition (APEC)*, 2021, pp. 1146-1152.

Space Science & Technology Evaluation Facility. S. Alvarez[1] and E. Jordan[2], [1]Aegis Aerospace, Inc., 17146 Feather Craft Ln., Ste 350, Webster, TX 77598, (Contact: sergio.alvarez@aegisaero.com)

Introduction: As the United States and the National Aeronautics and Space Administration (NASA) embark on a new phase of space exploration, Aegis Aerospace continues to blaze a trail for commercial, academic, and government entities to understand the Low-Earth Orbit (LEO) and lunar environments. The Space Science & Technology Evaluation Facility-First Flight (SSTEF-1) project, Aegis Aerospace's latest mission, is a fully-funded 10-kilogram payload scheduled to launch in the first quarter of 2025 with seven technology experiment partners. SSTEF-1 is a unique lunar testbed that will allow these aerospace companies and research institutions to progress their Technology Readiness Level (TRL) to 7 or 8 through lunar surface testing. As a pioneer of commercial lunar testing as a service, SSTEF-1 enables both active and passive experiments to experience the extreme lunar environment and understand its impacts. This allows SSTEF customers to analyze collected experiment data and potentially increase the reliability of their technologies. During development, Aegis Aerospace and our experiment partners are conducting trade studies to enhance lunar operations in extreme environments, thermal control, radiation exposure, regolith mitigation, and other lunar challenges. In addition to environmental trade studies, SSTEF-1 will explore additive materials to minimize the structural mass of the testbed since commercial lunar surface delivery prices are over $1MM/kg. SSTEF-1 will optimize its power and data resources via efficient avionics, novel electronics designs, and innovative software algorithms to maximize capacity without impacting volume or mass. SSTEF-1 will continue to evolve mission operation adaptability and flexibility by leveraging the Aegis Aerospace Payload Operations Control Center (POCC), which has served for several years operating space platforms and experiments. With this project, SSTEF-1 and future SSTEFs will facilitate further contributions from our aerospace partners to the exploration and development of the Moon while providing NASA with tangible engineering data, technology development, and the lunar environment exposure necessary to safely and successfully carry out sustained human exploration of the Moon.

In-Situ Reaction Monitoring for Lunar Applications Utilizing a Single Quadrupole Residual Gas Analyzer

Thomas T. Barnes III, Nilab Azim, Joel A. Olson, Tonyé N. Hale, Ray Pitts, Malay Shah, Annie Meier, and Jennifer G. Williams; NASA, Kennedy Space Center, FL (Contact: Thomas.barnes@nasa.gov)

Introduction: With a revived focus to create a permanent presence on the moon and in preparation for future Mars exploration, it is imperative that all resources are utilized to their fullest potential.[1] In-Situ Resource Utilization (ISRU) will be critical for future mission success as it would enable independent operation of missions while minimally relying on the complex supply chain created between the Earth, moon and Mars.

One of the most critical resources that have been identified for ISRU is the creation of liquid oxygen (LO_2) for not only breathable air, but also for rocket propellant. On the moon and potentially Mars, one of the most O_2 rich resources is in the presence of regolith.[2],[3] Although there are numerous minerals within regolith and various processes to extract O_2, this is not the scope of this paper.

Since the O_2 extraction method can vary, a critical standardized analytical method is needed to verify O_2 (or oxygenated precursor compounds) for extraction efficiency and purity. Our group utilizes a modified consumer off-the-shelf (COTS), Residual Gas Analyzer (RGA) Single Quadrupole Mass Spectrometer (QMS). Due to the current field mission requirements, the gas analysis module will need to rely only on mass-to-charge ratios (*m/z*) and peak intensities to differentiate and quantitate targeted gas-phase reactants or products, i.e. carbon monoxide (CO), carbon dioxide (CO_2), methane (CH_4) and hydrogen (H_2). However, due to solar wind implanted volatiles and various other compounds present in lunar regolith, such as nitrogen (N_2), helium (He), and deuterium (D_2), deconvolution and quantification of isobaric compounds becomes quite difficult. Specifically, the presence of N_2 makes quantification of CO, an oxygenated precursor, difficult due to both compounds having a peak at *m/z* 28.

Approaches to differentiate isobaric components: Initially, the solution to overcome isobaric overlap was to use isotopic ratios, particularly between carbon-13 and nitrogen-15. Although limited literature discuss isotopic composition and attempt to quantify the ratios, variation is particularly high and limited to a few lunar regolith samples. [3] The following were identified as potential approaches to quantify isobaric species, N_2 and CO, using our RGA.

Threshold Ionization. CO and N_2 both have peaks at *m/z* 28, but only N_2 is capable of producing a peak at *m/z* 7. [4] While a N_2 peak at *m/z* 7 is generally rare, instrument parameters can be optimized in order to maximize the peak intensity. Typically a standard ionization energy of 70 eV is used to monitor a batch process and would produce reliable results for a majority of the reactants or products that we are interested in quantifying. However, to analyze the rare molecular fragment of N_2 (N^{2+} at *m/z* 7), a different ionization energy may be beneficial. Threshold Ionization Mass Spectrometry (TIMS) will be explored to optimize the N^{2+} peak at *m/z* 7 by varying parameters such as ionization energy and pressure. Therefore, a quantitative value at *m/z* 7 will be used to determine the product gas concentration of N_2, which will be subtracted from the total concentration determined at m/z 28 enabling us to approximate the amount of CO.

Secondary Detector (infrared gas detector, IR). Another approach to quantitate and differentiate between isobaric components is to leverage alternative modes of detection. Unlike mass spectrometry, which generally uses a separation step prior to analysis (i.e. gas chromatography), IR produces energy that is specifically absorbed depending on the bond and configuration of the molecule. This technique could be leveraged since it is generally only active on non-symmetric molecules, i.e. CO. [5] Utilizing concentrations of CO determined from another detector could help correct concentrations of CO obtained from the QMS. However, the inclusion of another detector adds additional mission requirements, such as power, software changes and avionics updates that add additional cost and schedule requirements.

Acknowledgments: NASA JSC, KSC, GRC teams, and other Business partners working on the CaRD. Space Technology Mission (STMD), and STMD's Lunar Surface Innovation Initiative (LSII).

References:

[1] Artemis Lunar Exploration Program Overview, NASA HQ, https://www.nasa.gov/specials/artemis/ [2] Gibson E. et al. (1974) *Apollo lunar Sample analysis, NASA* [3] Mortimer J. et al. (2015) *ICARUS, 255, pg 3-17.* [4] Davies S. et al. (2014) Threshold ionization mass Spectrometry, Vacuum 101 , pg. 416-422 [5] CRC Handbook.

Drop Tanks for Lunar Propellant as a Lunar Metals Minimum Viable Product. N. J. Bennett[1] and A. G. Dempster[2], [1,2]Australian Centre for Space Engineering Research (ACSER), University of New South Wales (UNSW), Sydney, NSW, 2052, Australia. (Contact: nicholas.j.bennett@student.unsw.edu.au)

Lunar Propellant in Earth Orbits: An established use case for lunar propellants is in LEO for satellite orbit raising and lunar/interplanetary transfers. The viability of lunar propellant will be heavily influenced by the surface production scale and innovation required to meet demand, which is determined by transportation efficiency and the type of propellant delivered. Commercial IRRs are very sensitive the initial costs determined by production scale.

Often aerobraking is used to increase efficiency. The authors show that propellant delivery in lunar manufactured disposable tanks also increase efficiency, with a pressurized volume by-product. They also show that the effectiveness of aerobraking will likely be reduced as demand increases. This creates a potential opportunity for lunar manufactured propellant tanks to contribute to making large scale lunar propellant viable.

Tradespace: The scale of lunar propellant production required to meet demand, and thus its viability, is modulated by a trade space around delivery orbit eccentricity, delivered product (LOX or LH2LOX), drop tank CONOPs, and aerobraking.

The authors' earlier work for a NIAC study showed that propulsive delivery is more efficient than aerobraking at and above GTO like orbits.

If one delivers oxygen oxidizer one will more fully utilize electrolyzed water, or tune mixed water and regolith, propellant production. For water this can increase effective production by 40%.

One can also stage away empty tanks or deliver propellant "containerized" in drop tanks manufactured on the Moon. Supplying the SpaceX Mars project's 450,000 t/y of LOX in LEO would leave 430 ISSs/y of pressurized volume as byproduct.

Aerobraking Scale Problem/Lunar Drop Tank Opportunity: One can expect the effectiveness of aerobraking to face structural, capital, and operational challenges as scale increases, potentially creating an opportunity for lunar tanks.

A 1985 aerobraking Orbital Transfer Vehicle (OTV) could brake 7 t into LEO [1], 20 OTV flights to replace a SpaceX Starship Tanker flight. With reusability and inexpensive propellant SpaceX projects that flight operations costs will dominate.

Increasing capacity without raising peak heat requires increasing frontal surface area, the cube square law pancakes the OTV, incurring structural penalties. Low thermal and acceleration multi-pass aerobraking incur operational and capital penalties since more vehicles must be employed, in parallel, to achieve the same delivery rate.

Drop Tanks; Propellant and Pressurized Volume: One can stage away tanks after major burns, or at delivery, to substantially increase delivered propellant. Tanks left in orbits are pressure vessels, useful for propellant depots or habitable volume. One can trade propellant efficiency against delivered volume via the TEI CONOPs.

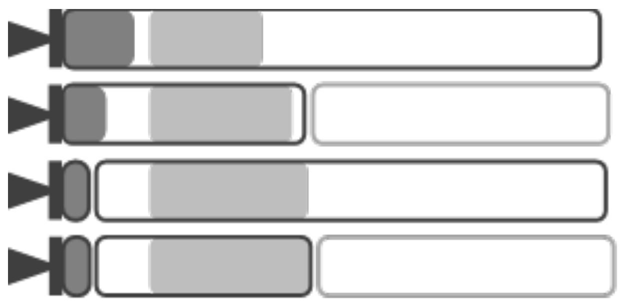

Fig. 1. LLO-LEO. Return (dark) & delivered (light) prop to scale. Baseline, TEI stage, LEO drop, TEI stage & LEO drop

Many lunar propellant production methods are parts of metal production pathways. Beneficiation of granular ice and regolith can separate free Fe. Metals are a common/targeted by-product of regolith oxygen production.

Results: The authors derive the delivery efficiency for scenarios with delivery orbits ranging from LEO through to LDHEEOs, these orbits can be oriented for lunar or interplanetary injections. LDHEEOs have been used in NASA Mars plans to soak up the excess delta-v that a volume-constrained launch of hydrogen propellant entails. O_2 burning vehicles in HEEOs could be customers for hydrogen-constrained lunar propellant production.

Conclusion: The authors propose CONOPs that bridge the gap between best case aerobraking and monolithic reusable propulsive delivery. Propellant tanks are an interesting lunar minimum viable product because propellant mass dominates and needs containers, pressure vessel additive manufacturing proof of concepts exist, metals are a by/co-product of many propellant production concepts, and disposable tanks improve the efficiency of resource and propellant utilization and thus increase lunar propellant viability.

[1] Scott C.D., et al. (1985) No. NAS 1.15: 58264.

Pre-Manufactured Cementitious Lunar Landing Pad Alternative. D. Boll[1] and P. Suermann, Ph.D., P.E., F. ASCE [2], [1]Texas A&M University, 789 Ross Street 3137 TAMU Langford Building A, [2]Texas A&M University, 789 Ross Street 3137 TAMU Langford Building A. (Contact: Dakota.Boll@tamu.edu)

Introduction: Proposed lunar infrastructure is largely based on planned lunar ISRU production. Prior to large-scale of extraction, within the scale of 100-1000 megatons annually[1], several equipment supply missions will land on the lunar surface to deliver the autonomous machinery. Leading designs by several groups, both private and government, have produced landing pad designs based on 3D printed regolith. These pads will be cementitious in nature and will be produced by mixing the regolith with an admixture compound[2]. Since these pads will require extensive autonomous machinery to be constructed, an alternative pad design was considered using pre-manufactured materials.

Parameters: Nasa has preliminary parameters mentioned by Dr. Corky Clinton, of Marshall Space Flight Center[3] for lunar landing pad dimensions. The pad is to be 25 feet in diameter, possibly surrounded by a 25 feet diameter apron, with vertical blast shield walls. The purpose of these parameters is to guide research (DM-2) into 3D printed landing pads and evaluate capabilities of robotic ISRU construction. These parameters will be considered in the design of the alternative design proposed this research so that the two methods of construction may be compared. Figure 1 shows a proposed landing pad by Dr. Clinton[3].

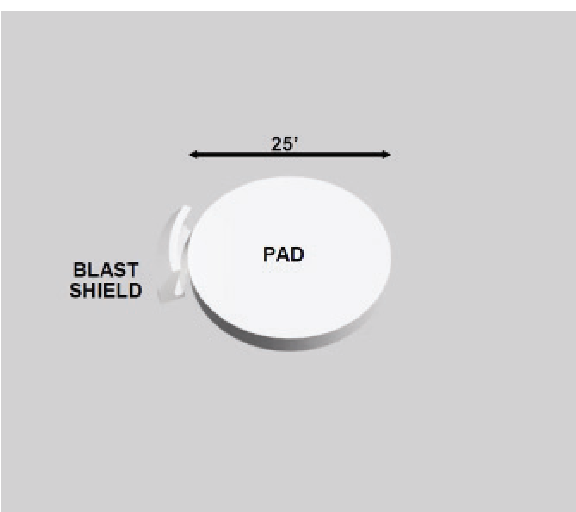

Figure 1: Lunar laning pad parameters including pad and blast shield, with no dust control apron.

Research Goal: Serving the function to provide a controlled landing surface for equipment missions prior to production of ISRU materials, a pre-manufactured landing pad design will incorporate characteristics relating to dust control and reusability. Dust control is essential to equipment longevity, astronaut health, and catastrophic failure mitigation. Artemis missions will require landing areas and roadways that exhibit dust control characteristics. As materials transportation to the lunar surface is a premium, and the lunar environment exhibits extreme temperatures, a robust and efficient material is needed for lunar dust control.

Material Testing: Concrete cloth, a rolled cementitious material primarily used for water and fire protection, will be tested for strength in both original unhydrolyzed condition, as well as treated with dry-mix soil stabilizer. The testing methods performed will follow ASTM D6685[4] "Standard Guide for the Selection of Test Methods for Fabric Formed Concrete". Standards used will be D4354 "Practice for Sampling of Geosynthetics and RECPs for Testing", D4533 "Test Method for Trapezoidal Tearing Strength of Geotextiles", D4595 "Test method for Tensile Properties of eotextiles by Wide-Width Strip Method", and D5321 "Test Method for Determining the Shear Strength of Soi-Geosynthetic Interfaces by Direct Shear".

Results: As proposed and proven by Lee in 2012[5], cementitious materials can be a viable option for lunar landing pads. Whereas Lee proved the pads met strength requirements to supports landing modules, his work did not provide dust control measures. If proven successful in strength testing, concrete cloth and dry-mix soil stabilizer have potential to meet the need of temporary landing areas and roadways for missions to Shackleton Crater.

References: [1] Sanders J. (2022) *LSIC*, Regolith to Rebar Workshop. [2] Mueller R. (2016) *ASCE Earth and Space*, conference proceedings, pp 354-377. [3] Clinton C. (2022) *LSIC,* Excavation and Construction January subgroup meeting. [4] ASTM Compass. (2015) *ASTM International*, ASTM D6685-01. [5] Lee J. et al. (2012) *ASCE Earth and Space*, NASA/ASCE workshop on granular materials in space exploration, pp 128-134.

What GPS really costs and implications for the development of a lunar satellite navigation system.
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Introduction: There is significant worldwide interest in developing a satellite navigation system for the Moon [1]. The European Space Agency Moonlight initiative has proposed creating a partial lunar satellite navigation system starting in 2025, with a full system slated to be operational by 2035. In September 2021, NASA published a draft of its LunaNet Interoperability Standards, designed to ensure that satellite navigation signals from different commercial providers are interoperable.

Both of these initiatives face a daunting fact - building and maintaining a satellite navigation systems is expensive. How expensive? For fiscal year 2022 the United States of America's Presidential budget requested 1.8 billion United States Dollars (USD) for the Department of Defense Global Positioning System (GPS) program [2].

Methods/Discussion: Given the unlikelihood that any government agency will invest a similar amount in a lunar navigation system, what tradeoffs will be necessary? To answer this question, we will discuss what the USD 1.8 billion funds in the GPS system. We will examine options for reducing some of those costs via less expensive technologies (particularly clocks and smallsats), and minimizing the ground control segment that is often overlooked in discussions of satellite navigation system costs. We will conclude by outlining the tradeoffs between cost, reliability, availability, accuracy, and time to first navigation solution that changes to the existing model will likely entail. This will give prospective lunar explorers an idea of how a lunar satellite navigation system may differ from GPS, and how this will impact lunar surface operations.

References: [1] Schönfeldt M. et al. (2020) "Across the Lunar Landscape – Exploration with GNSS Technology." Inside GNSS, 02 October 2020, https://insidegnss.com/across-the-lunar-landscape-exploration-with-gnss-technology/. [2] National Coordination Office for Space-Based Positioning, Navigation, and Timing (2022) "Fiscal Year 2022 Program Funding." GPS.gov, 02 March 2022, https://www.gps.gov/policy/funding/2022/#dod-approps.

A compact, low-pressure, low-voltage neutron detector array for lunar volatile surveys. C. B. Shahi[1], J. J. Su[2], M. A. Coplan[1], A. K. Thompson[3] and C. W. Clark[1,3], [1]University of Maryland, College Park, MD 20742, [2]Systems Engineering Group, Inc., Columbia, MD 21046, [3]National Institute of Standards and Technology, Gaithersburg, MD 20899. (Contact: charles.clark@nist.gov)

Introduction: Absorption of thermal neutrons by ^{10}B results in reaction products ^{7}Li, α with excess energy of 2 MeV. When these energetic products traverse noble gases at atmospheric pressure, they generate noble-gas excimer dimers that emit far-ultraviolet (FUV) radiation in the wavelength range of 120 – 170 nm. The ground states of the excimer dimers are unbound, so the noble gas is transparent to the FUV. Up to a 40% of the nuclear reaction energy is channeled into FUV emission, yielding 10^4 photons per neutron absorbed. [1-3]

Basic detector cell: Our basic detector cell contains μm-thick films of ^{10}B, deposited by electron-beam evaporation on aluminum substrates, in a physics package of ~ 10 cm^3 volume filled with Xe gas at 10^5 Pa pressure. The FUV light is detected by silicon photomultipliers.

Multifunctional cellular detector array: We make compact arrays of such cells, affixed with various high-density polyethylene (HDPE) and cadmium (Cd) foil attachments. We also incorporate "sterile" cells, end-to-end equivalent to the ^{10}B cells except their boron films consist of high purity ^{11}B, which does not react with neutrons but has the same response to electromagnetic radiation as ^{10}B. Response of the sterile cells provides thus provides a measure of non-neutron background radiation in the lunar environment.

Deployment: Variation of HDPE and Cd attachments foil attachments across a diverse detector array enables one to infer properties of the phase space distribution of local neutron fields and to sense depletion of the epithermal neutron spectrum by hydrogen volatiles. We will show studies of these in on platforms of simulated lunar basalts. Detector arrays could be stationed aboard rovers or in fixed positions.

References: [1] Hughes P. P. *et al.* (2010) *Appl. Phys. Lett. 97*, 234105. [2] McComb J.C. *et al.* (2014) *J. Appl. Phys. 115*, 144504. [3] Graybill J. R. *et al.* (2020) *Applied Optics 59*, 1217.

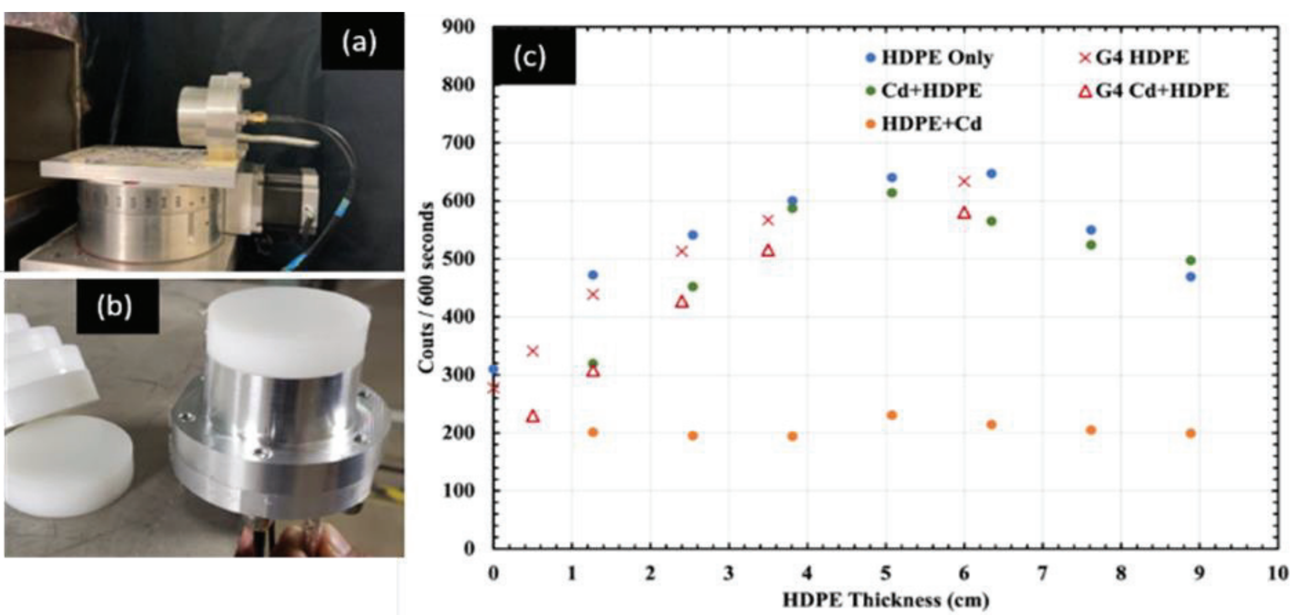

Figure. (a) A basic cell faces the NIST Californium Neutron Irradiation Facility beam that emanates from the output port on the left. **(b)** The cell affixed with ½'' thick HDPE. **(c)** Neutron counts vs. attachment thickness, with and without a Cd foil between the HDPE stack and the front face of the detector. Circles: experiment; crosses and triangles: Geant4 simulations.

Passive Dust Mitigating Materials Evaluation Supporting NASA's Patch Plate Materials Compatibility Assessment Project

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Introduction: Lunar dust is one of the main challenges for long term exploration and habitation on the lunar surface. Exposure to this jagged, abrasive, electrostatic and highly adhesive dust will lead to contamination and failure of components, from radiators and solar arrays to spacesuits and interlocks. With the Artemis mission planning to send humans to the moon potentially in 2024, there is an urgent need to develop methods to mitigate the effects of lunar dust to enable mission success. An important strategy is passive dust mitigation, in which the material surface itself can reduce dust adhesion. This may be an intrinsic property of the material or might be imparted by surface modification such as a coating, topographical modification, or both. The Patch Plate Materials Compatibility Assessment Project under the Space Technology Mission Directorate's Dust Mitigation Program aims to develop passive dust mitigating materials technologies, demonstrate their performance in ground-based tests simulating the lunar environment, and finally fly them to the lunar surface for actual evaluation. For the Patch Plate task at NASA Langley Research Center (LaRC), a variety of materials and surfaces were examined for lunar dust simulant adhesion using a custom-built adhesion testing system. Some of these materials had extensive space-heritage, while others were novel and fabricated in house. Laser patterning was also evaluated as an approach to controllably alter the topography. Evaluation of a broad array of potentially useful materials and surface modified materials will be performed followed by down selecting the materials and surfaces that exhibited promising dust adhesion mitigation performance. A brief overview of the dust adhesion test results and other characterization conducted for the different classes of materials for passive dust mitigation will be discussed.

Enabling Science and Exploration Objectives with Lunar Services. C. M. Edwards[1] and T. Cichan[1], [1]Lockheed Martin Space. 12257 S Wadsworth Blvd, Littleton, CO 80127 (Contact: christine.m.edwards@lmco.com)

Abstract: As part of the Artemis era of space exploration, space agencies will be working together with their industry partners to establish systems and infrastructure that enable sustained lunar missions and develop capabilities for Mars. The planning for this next phase is possible now that Orion and the Space Launch System are about to perform their initial missions together, the initial Gateway elements are in design and production, and the set of regular lunar robotic landing missions from a diversity of countries and companies has begun. Each mission to the lunar surface, both crewed and robotic, offers the opportunity to perform new scientific investigations and demonstrate new technologies and operations. And the barrier of entry for these investigations can be lowered with the delivery of systems that can provide power, communications, and mobility services for these missions.

For this presentation, we will discuss how various lunar science and exploration objectives can be enabled by power, communications, and mobility services. A list of objectives that are being established for the Artemis program will be shown, along with an analysis of the kinds of capabilities that other systems can provide as a service to enable achieving those objectives. Also, the capabilities of several systems that are under development will be discussed, and how those capabilities can be provided as a service. These systems include vertical solar array technology (VSAT), mobility vehicles, and communication satellites. This infrastructure will be a key aspect in supporting growing capabilities on the lunar surface, lowering the barrier of entry, and both enabling the Artemis missions and providing the basis for a lunar economy.

Microwave Structure Construction Capability for the Moon. M. R. Effinger, NASA Marshall Space Flight Center (MSFC), Huntsville, AL (Contact: Michael.R.Effinger@nasa.gov)

Introduction: Infrastructure on the Moon utilizing in-situ resources is necessary for a permanent base. To consolidate the lunar regolith into infrastructure, a heating source to achieve a glass-ceramic. The most efficient means to volumetrically heat regolith is with microwave energy. The Microwave Structure Construction Capability (MSCC) element within Moon to Mars Planetary Autonomous Construction Technology project is developing technology and conops to build infrastructure with microwave energy [1, 2].

Overview: MSCC is pursing paving and brickmaking processes for infrastructure formation. For the paving method, the microwave system would move across the regolith and sinter the regolith in place. In order to do this, there is site preparation necessary. Rocks would need to be removed from the construction area. The site would then be leveled and compressed. Bearing strength, dielectric, and angle of repose testing would occur. Microwave sintering would commence at that time. Placing additional material on top of the sintered material would occur after the first layer is complete. The load sustaining capability, coarse porosity, & geometry would be characterized with instrumentation for the final product.

Multiple organizations are working to develop microwave sintering. Small scale microwave sintering is being done at NASA Jet Propulsion Laboratory. Large scale microwave sintering is being done at Alfred University and MSFC. Full-scale testing will be done at MSFC in a 20ft diameter vacuum chamber. Large-scale and full-scale testing will generate plates with horizontal and vertical fused joints for characterization. That characterization will feed modeling for performance and life prediction for resulting infrastructure. Non-destructive and destructive evaluation will occur. Critical flaw size determination will also be done.

MSCC is evaluating multiple hardware configurations. Microwaves can be generated from two different sources: magnetron and solid state. Solid state is baseline for Mars. MSCC is evaluating different applicators, the location where microwaves exit from the hardware and are transmitted into the regolith or simulant. Horns, leaky wave guide, and wave guide array are current options being pursued. Other options are being considered for the future to increase system performance and efficiency, product quality, and reduce risk.

In order to be flexible to the composition and dielectric properties of various locations on the Moon, MSCC is planning to characterize major regolith constituents to estimate microwave sintering protocols with models.

High temperature bakeout procedures for simulants are being developed to mitigate non-lunar behavior of the simulants and ensure more accurate microwave sintering. New highlands simulants are being developed [3].

Extensive simulant testing is being done to support all this development including, but not limited to: Differential Thermal Analysis (DTA), Differential Scanning Calorimeter, and Thermal Gravimetric Analysis (TGA) in vacuum and inert, particle size, particle shape, and surface area testing, Raman spectrometry, optical and electron microscopy, cathodoluminescence imaging, mass spectrometry with respect to temperature in vacuum and inert, chemical analysis, etc.

Furnace sintering tests are being conducted to better define the sintering window that will feed into the microwave sintering testing and protocol development.

References:

[1] R. G. Clinton, et al. ASCEND 2021.

[2] M.R Effinger, et. al. Lunar Surface Innovation Consortium Fall Meeting, November 4, 2021.

[3] Doug Rickman, Holly Shulman, Matthew Creedon, & Mike Effinger. 53rd Lunar and Planetary Science Conference, March 7-11, 2022.

The Gandalf Staff: A Mobile, Self-Powered Platform for Lunar Surface Exploration.

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Introduction: The Artemis program is planning to deliver crew and cargo to the lunar surface. The Gandalf Staff is intended as a flexible, auxillary, self-powered platform outfitted with various components to support both crew Extra-Vehicular Activity (EVA) traverses and science exploration for long-term instrument data collection.

Gandalf Staff: The Gandalf Staff is an early prototype system developed over FY'21/FY'22 using NASA Science Technology Mission Directorate (STMD) Center Information Fund (CIF) Internal Research and Development (IRAD) grants to design, build and test "proof-of-concept" components. These components include a 24v battery powered monopole that powers a suite of subsystems, including a Graphical User Interface (GUI) for crew, surface voice and data communications, Lunar Search and Rescue (LunaSAR) navigation and communications, LiDAR, field site external lighting, 360-degree camera, and a geothermal instrument for measuring subsurface temperature gradient. The staff can be carried independently by an Extra-Vehicular Activity (EVA) astronaut, or can be mounted into a tripod for "hands free" support at a surface site being investigated. The staff can be attached to an external solar array and power storage system for long-duration operations. [1,2]

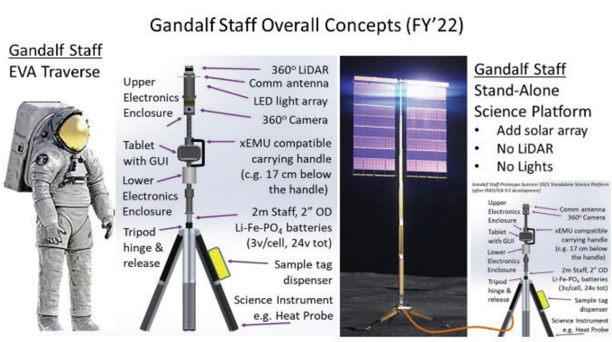


Figure 1: Gandalf Staff Components

Collaboration: To make rapid progress in the 1st year (FY'21), and also to demonstrate innovative project management techniques, NASA guided a private industry partner, T STAR, in leading Capstone Engineering student teams at Texas A&M University (TAMU) for proof-of-concept development and testing. Year1 was focused on developing the core staff (power/lighting/camera/LiDAR) supporting crew EVA and sample curation. For the 2nd year (FY'22), NASA is again collaborating with TAMU/TSTAR student teams to prototype new components. In Year2, capabilities are being enhanced for EVA support (2nd generation lighting system and handheld LunaSAR device) while adding new features for science instrumentation (subsurface geoprobe). This heat probe is based upon Apollo heritage but modified to measure subsurface volatile ice regimes at the Artemis landing site. This science instrumentation, developed in conjunction with an external solar array and energy storage system, provides a platform that is similar to the Apollo Lunar Surface Experiment Package (ALSEP) [3].

The Gandalf Staff team is also collaborating between NASA centers. The LiDAR subsystem is supported with expertise and funding from MSFC/Michael Zanetti, who provided expertise and mentoring for the TAMU student team and a graduate student studying point cloud data integration. The LunaSAR device is supported by GSFC/Cody Kelly with expertise and mentoring of the TAMU student team.

Project Development Summary

FY'21 IRAD Funding

Develop proof-of-concept for initial electronics

- Power: 24v LiFePO4 rechargeable battery system
- Data Comm: Using 802.11n
- Voice Comm: Using UHF
- User Interface: Using tablet and GUI
- LiDAR: Using OUSTER OS0 system
- Lights: 40 LEDs bulbs on a custom 4-card system

FY'22 IRAD Funding

Continue proof-of-concept for more electronics systems and create models for field testing and demonstrations

- Power: Develop solar array & battery sysem
- Power: Create rapid replacement battery packs
- Science: Build/test a geothermal subsurface probe
- Lights: Evolved lighting system design and testing
- LunaSAR: Create new EVA handheld unit to send emergency message to simulated satellite network
- Efficiency: Reduce overall complexity and mass

References: [1] Evans, M. E., et al. (2020), The Artemis "Gandalf's Staff" Science Suite for Crew EVA Lunar Field Geology, LPSC. [2] Evans, M., et al. (2021). Initial Prototype Work on Artemis "Gandalf's Staff"- Science Suite on a Lunar EVA Walking Stick, LPSC. [3] NASA (2008), "Apollo Lunar Surface Experiments Package (ALSEP), from https://www.hq.nasa.gov/alsj/HamishALSEP.html

Planetary Resource and In-Situ Material Habitat Outfitting for Space Exploration (PRISM-HOUSE)
D. M. O'Rourke[1], M. Forlife[2], P. Corwin[3], and T. Nguyen[4], [1]Colorado School of Mines, 14361 W Yale Pl Lakewood, CO, 80228, [2]Colorado School of Mines, 419 Sevilla Drive, Colorado Springs, CO 80911, [3]Colorado School of Mines, 1500 Illinois St, Golden, CO 80401 [43]Colorado School of Mines, 1500 Illinois St, Golden, CO 80401. (Contact: forlife@mines.edu and pecorwin@mines.edu)

Introduction: The PRISM-HOUSE team participated in the NASA Moon to Mars Exploration Systems and Habitation (X-Hab) challenge for 2022 [1] on behalf of the Colorado School of Mines. Our task was to design a system to deploy, outfit, and operate a habitat on the surface of the Moon, while utilizing in-situ lunar resources as much as possible. We proposed a design, identified the requirements, and investigated significant considerations, analysis, and technical capabilities of interest. The team is currently producing deliverables and conducting tests to evaluate design feasibility. The primary objective of the system is to provide a safe and livable habitat near the lunar south pole with an optimized balance between delivered material and utilization of in-situ resources. A preliminary systems engineering design has been completed and reviewed by NASA, key system risks identified, and test plans defined to mitigate some of these risks. These test plans will be executed over the next several weeks and results evaluated to determine final risks to the system and recommendations for next steps.

Project Aim: Produce a design study of feasible concepts to deploy, outfit, and sustain a lunar habitat for up to four astronauts utilizing in-situ lunar resources to maximize on-site additive manufacturing, by leveraging expertise of industry partners in each key area.

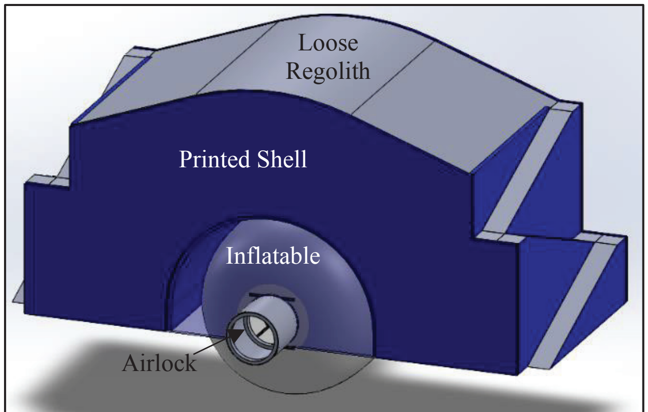
System Preliminary Design: The PRISM-HOUSE overall system has been divided into three primary focus systems for the purposes of this project.

External Structures & Environmental Protection

Consisting of a shell structure created using additive manufacturing with lunar regolith as the feedstock, loose regolith material backfilled into the shell structure, and openings designed to allow ingress and egress, the ESEP system provides protection from radiation and micrometeorites.

Human Interior Goods

Objects interior to the habitat used by human occupants, including floors, walls, chairs, tables, small tools, utensils, and replacement parts for other systems. These objects are created utilizing additive manufacturing techniques with regolith feedstock and binding agents.



PRISM-HOUSE Overall System Concept

ECLSS & Remote Outfitting

Environmental Control and Life Support as well as rovers and other automation equipment which allows the system to be fully deployed, operational, and life-sustaining prior to astronaut arrival.

Test Plan: Scaled external deployment test, using lunar-rated rover prototype to simulate transport and placement of external equipment, chemical leaching test of regolith-simulant printed objects to determine suitability for use with food and water to be consumed by astronauts, design and strength test of free-form 3D printed interior structures, habitat 3D model and simulation of daily activities, and 3D printing tests of external shell using regolith simulant.

Anticipated Results: Reduction of key risks and support of quantitative metrics for subsystem masses, installation and commissioning times, habitat configuration, concept of operations, and expected percentage of system mass which can be provided through the use of in-situ materials. Also identified will be critical assumptions made with supporting documentation and associated recommendations for next steps to determine overall design feasibility.

References: [1] NASA (2021) https://www.nasa.gov/exploration/technology/deep_space_habitat/xhab.

Localization and Mapping Software for Diverse/Remote Robotic Operations.

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Introduction: NavAbility is a young robotics software company, who partners with robotic integrators and equipment manufacturers who require localization/mapping/navigation software. NavAbility is developing next generation algorithms and techniques that fundamentally support distributed system design and robustness. NavAbility is working to make it easier, faster, and more cost effective to bring advanced navigation AI software to new or existing platforms. NavAbility products include open libraries, the NavAbility Platform, and domain expertise. NavAbility started from the community at MIT [1,2].

Conventional to Next-Gen Navigation: The software for navigation systems today are highly fragmented, yet share many fundamental ideas and constructs. NavAbility was established to better harmonize the common scientific aspects across most localization and mapping systems by embracing a hybrid open-source and proprietary philosophy. We at NavAbility, along with the community, continue to develop and advance a common algorithmic implementation that can perform algebraically equivalent operations to conventional attitude heading reference systems (i.e. Kalman Filter), inertial (preintegration) navigation systems [3], INS/GPS, visual odometry systems, terrain relative navigation, range-only systems, simultaneous localization and mapping (SLAM), structure from motion and bundle adjustment systems, as well as envisioned future methods that rely heavily machine learning and neural network techniques. NavAbility uses a factor graph modeling language as the scientific underpinning that allows algorithmic consolidation of many existing methods. NavAbility freely shares its core solver source code [4] for better transparency, community involvement, and ultimately higher quality solutions.

Distributed / Remote Architectures: Navigation systems form an integral part of robotic automation systems and can therefore significantly benefit from a architectural design that fundamentally enables distributed operations over varying quality network connections [4]. By again leveraging the factor graph abstraction, NavAbility is able to develop systems that exhibit strong harmony and symmetry in design, communication, compute, and memory over divergent nodes in a network. Our approach significantly simplifies how various agents interact with the NavAbility Platform.

Robustness: Distributed for us also implies a wide aperture in terms of multi-sensor data. The origin of measurement data, including human input cues, or (possibly contradictory) prior data should all be available for joint inference towards a stable, reliable, robust localization and mapping solution. Furthermore, the timeliness of computation and results too are major factors for design, and can vary from application to application. NavAbility uses state of the art algorithms for performing non-Gaussian (multi-modal) inference on factor graphs, with a variety of advanced features for recycling older computation or future trajectory planning and multi-robot data sharing.

Non-Gaussian Factor Graphs are a probabilistic modeling language which is well suited to describing measurement events in both human and machine readable form. NavAbility is working to develop the premier open standard for factor graph based data fusion software of the future. Especially for cases with ambiguous and uncertain data. Our approach supports both batch and real-time processing use-cases.

References:

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[2] Fourie, D. (2017): "Multi-modal and Inertial Sensor Solutions for Navigation-type Factor Graphs", Ph.D. Thesis, MIT/WHOI.

[3] Fourie D., Leonard J. (1996): “Inertial Odometry with retroactive sensor calibration”. US Patent 10,317,214.

[4] Contributors, Ecosystem, NavAbility (2022), “Caesar.jl Solver, v0.12.0”*, Software, Online: https://github.com/JuliaRobotics/Caesar.jl*.

Wireless Power Transfer on the Lunar Surface: Experimental Results Using Magnetically Coupled Resonators in Presence of Lunar Simulants. S. M. Garman[1] and J. R. Smith[1,2], [1]Department of Electrical & Computer Engineering, University of Washington, Seattle, WA, [2]Department of Computer Science & Engineering, University of Washington, Seattle, WA. (Contact: shantig@uw.edu)

Introduction: Wireless power transfer using magnetically coupled resonators (MCR) is widely employed in biomedical and consumer electronics applications and has been deployed successfully in Earth-based mobile applications, such as UAV recharging and warehouse robot fleet charging scenarios [1-4]. A primary advantage of MCR is its ability to maintain high power transfer efficiencies even with significant misalignments between power transfer antennas. MCR is one technology under investigation for lunar surface power infrastructure, specifically for charging mobile units from a base station [5]. Presence of lunar regolith and fine metallic particles with iron content is an important consideration for wireless power transfer using MCR, because lunar dust adhesion to the power transfer antennas could cause loss of signal power and antenna detuning due to interaction between metallic iron in the regolith and the MCR's magnetic field.

In this work, we present experimental results for wireless power transfer efficiency and frequency response of the power transfer antennas in the presence of four different lunar simulants and two iron powders. Lunar simulants used include LHS-1, LHS-1D, JSC-1A, and OPRH4W30. Experimental results with four lunar simulants show minimal impact to power transfer efficiency and frequency response of the resonant coils, while results with equivalent amounts of pure iron powder show measurable impact to both parameters.

Experimental Setup: A wireless power transfer system from WiBotic, Inc. was used for all tests, including a TR-301 transmitter, OC-251 charger, TC-200 transmit antenna coil, and RC-100 receive coil. A rechargeable UAV battery was used as a target load. Power transfer efficiency was measured using WiBotic's control software, and frequency response was measured with a nanoVNA.

Results & Discussion: Lunar simulants are shown to have minimal impact to power transfer efficiency and frequency response of the resonant coils, while certain amounts of pure iron powders show significant impact to both parameters.

Impact of Lunar Simulants. Results show the system is able to charge at ≥98.5% of peak efficiency with lunar simulants in amounts up to 1kg coating the power transfer antennas (surface

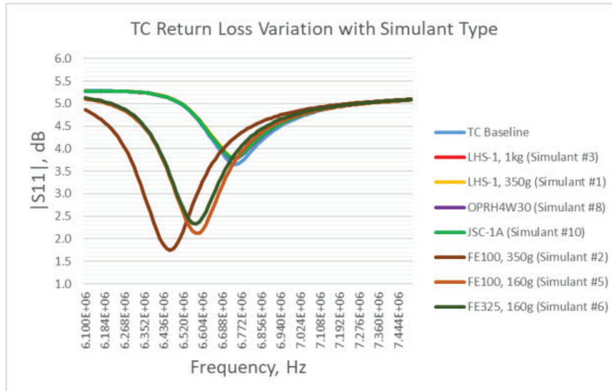

Figure 1. Measured frequency response of transmit coil return loss (S_{11}) in presence of lunar simulants and iron powders.

density of 1.4g/cm^2). Frequency response results show negligible shift of the antenna coil resonance due to presence of lunar simulants (see Fig. 1).

Impact of Fine Fe-Based Metallic Particles. Results show impact to power transfer and frequency response is proportional to surface density of iron powder present. Full power transfer is achieved even in the presence of iron powder at a surface density of 0.1g/cm^2, while a very dense sample of 1.4g/cm^2 blocks all power transfer, effectively acting as a solid metal sheet. Similarly, frequency response data show a shift to the antenna coil resonance which is proportional to the amount of iron powder coating the coils (see Fig. 1).

Conclusion: Wireless power transfer using magnetically coupled resonators (MCR) in the lunar environment should be feasible, and effects of regolith on wireless charging appear manageable, enabling new wireless charging scenarios for lunar surface power infrastructure.

Acknowledgments: This work was conducted as part of NASA's Tipping Point program together with Astrobotic, Bosch Research, and WiBotic, Inc. *For disclosure of competing financial interest, see http://sensor.cs.washington.edu/disclosure.*

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Highlighting the Need for In-Situ-Derived Propellants for Cislunar and Near-Earth Applications

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In-situ-derived cryogens and cryogenic fluid management have been a large focus of recent NASA attention. For example, the 2020 NASA Tipping Point distributed $256 million of the $370 million Tipping Point budget to companies for cryogenic projects [1]. While cryogenics provide high thrust and a specific impulse typically higher than mono and bi-propellants, they fit only a narrow use case involving large scale, high power, complex systems over short periods. This leaves many spacecraft form factors that provide the instrumental building blocks of lunar infrastructure and support without a propellant that can be created from lunar resources, generating issues with long term sustainability. This results in a need for a storable, high impulse propellant derived from lunar resources. Up to this point, little work has been undertaken by the industry to satisfy this need, but based on a number of previous studies, Orbit Fab believes that high-test peroxide (HTP) is the best and only option for a storable high impulse ISRU derived propellant in cislunar space, and as such is developing a system capable of producing HTP from water.

This work will explore the use cases for the two major high-impulse propellants that can be created from Lunar resources: bipropellant hydrolox, and monopropellant HTP, and bring more clarity to their useful market and logistics segments within the cislunar economy. The propellants will be analyzed with respect to various spacecraft size classes, mission concepts of operations, storage requirements, risk margins, and anticipated market needs currently expected to emerge. The expectation is that cryogens will remain the obvious choice for large spacecraft performing high delta-V escape transfers, but HTP will represent a large market share across smaller and longer term spacecraft performing operations in the cislunar region, which do not have a long term thermal solution or size, mass, power, and cost (SWaP-C) allocation for a cryogenic fluid management system. The exact breakeven points across different spacecraft scales and delta-V requirements will be a critical outcome of this work, to help further define the relative priority that each type of propellant should hold when it comes to ISRU funding.

To sustainably fulfill this market segment and prove the feasibility and SWaP-C of HTP compared to non-ISRU storables, such as hydrazine, Orbit Fab's HTP Production System which generates HTP from water, can be combined with other extraction and water purification processes in order to resource-effectively produce HTP propellant on the surface of the Moon from icy regolith. These combinations can create an end-to-end supply chain that is currently being examined with a growing number of collaborators who are coming onboard with the HTP architecture. A unique finding is that when comparing the relative SWaP-C, it is estimated that a demonstration of this technology on the surface of the Moon could cost at least 10 times less than the demonstration of a comparable system designed to produce and store cryogenic propellant. Such a mission could occur in the next few years. Because of this, the authors believe that HTP represents a low-cost and low-risk development that requires greater attention and funding. The goal of this work is to promote that idea by demonstrating the valuable use cases of HTP to sustainably create the required architecture for the cislunar economy to best flourish.

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Title: Ceramic Oxygen Generators – An Emerging Technology With Applications for ISRU

John Graf (Johnson Space Center), Clinton Cragg (Langley Research Center)

Abstract: The NASA Engineering Safety Center (NESC) is sponsoring a fast paced technology insertion activity. Ceramic ion transport membrane technology has been studied in a research setting for decades, the NESC sponsored activity develops an oxygen generating system with sufficient technical maturity to make quantitative assessments about ceramic oxygen generation (COG) technology for different applications. NASA's initial application for COG technology is spacesuit oxygen tank recharge. NASA requires high pressure (>200 bar) high purity (propellant grade) oxygen for extended EVA operations. The solid state nature of the COG, and the reliable purity of the oxygen product makes COG technology a good fit for the EVA application. NESC's Medical Ceramic Oxygen Generator (M-COG) project addresses global health applications. Hospitals in remote locations suffer lack of access to oxygen – cryogenic oxygen and cylinder oxygen suffer transportation problems, and oxygen made on site using pressure swing adsorption technology suffers reliability problems. The solid state nature of COG may enable reliable production of oxygen on location, at a remote hospital. This presentation considers the possibility of using COG technology to support ISRU. Some ISRU processes produce a product that is mostly oxygen, but does not meet propellant grade purity requirements. COG technology could receive this "mostly oxygen" stream, purify it, pressurize it, and make propellant grade oxygen. COG technology work with process streams that are highly contaminated.

Metallic Environmentally Resistant Coating Rapid Innovation Initiative. A. R. Gray[1] and S. Rengifo[2], [1]Marshall Space Flight Center, 4602 Martin Road SW, Huntsville, Al 35808, [2]Marshall Space Flight Center, 4711 Apollo Street, Huntsville, Al 35808. (Contact: annette.r.gray@nasa.gov)

Introduction: Lightweight alloys such as aluminum (Al) and titanium (Ti) are often specified for space systems to minimize mass while maintaining structural integrity [1,2]. Such alloys however, have poor tribological response (high friction and wear), especially in extreme space environments, which becomes worse with the additional presence of lunar regolith. This leads to short lifetimes and premature failures that will ultimately limit long term operations on the lunar surface [2]. This project is addressing this technology gap by developing advanced wear- and radiation-resistant coatings for lightweight parts to extend the lifetime and sustainability of both lunar and Martian assets.

The focus of this effort was to explore both new and existing coating technologies, including material formulations and deposition methods. Several material options were considered for their wear resistance and fracture toughness and the following were chosen: Boron Nitride-Aluminum (BN-Al), Nickle Titanium (NiTi), Aluminum Oxide (AlO3), Ti64 with hBN at 2 and 10 vol percent (Ti-2vol%hBN and Ti-10vol%hBN). The deposition techniques chosen for this project are high pressure cold-spray (CS) and ambient and vacuum plasma-spray (APS and VPS) [3,4,5]. BN-Al, NiTi, Ti-2vol%hBN, and Ti-10vol%hBN were applied with all three deposition techniques, and AlO3 was applied only using the APS deposition technique. A tungsten disulfide (WS2) film was applied to the NiTi VPS coating.

The coating and deposition technique configurations are being tested against several end-use performance parameters. The parameters include the capabilities of the coatings under wear environments such as regolith simulant, thermal cycling, vacuum, and exposure to ionizing particle radiation. Wear tests include pin on disk, three-body abrasion, and surface erosion by high velocity regolith impacts.

Testing of these configurations is being performed in three phases with down selections between each to reduce the number of configurations for the higher fidelity phases. Phase I involves a series of environmental exposures of flat samples, followed by pin on disk and three body abrasion wear testing of exposed and virgin (unexposed) samples for comparison. testing of the virgin samples, and poor performance during the coating processes, allowed for some configurations to be eliminated early in this phase. Ti-10vol%hBN could not be applied using CS application and NiTi could not be applied using APS or CS application so these configurations did not get tested. BN-Al showed poor performance in the virgin sample testing and was eliminated early in the testing process. AlO3 on Al substrate did not survive thermal cycling, but wear testing is continuing for AlO3 on Ti substrate. A more detailed analysis is being conducted to further reduce the number of configurations for phase II and III. Phase II testing will include conventionally and additively manufactured substrates with vacuum pin on disk and surface erosion testing. In phase III, the coatings will be applied to three mechanism types: channel and slot, ball and socket, and a hinge joint. Each will demonstrate a different type of wear incidence. The mechanisms will receive environmental exposure and be actuated in vacuum with regolith simulant. This testing will help to determine which coating could withstand operation on the lunar surface

The mechanisms and their base materials are of direct interest to the end users and infusion points: the Human Landing System (HLS) and the Lunar Surface Innovation Initiative (sustained lunar surface operations). This technology development project is based out of Marshall Space Flight Center, has partnered with Florida International University (Miami, FL) and Plasma Processes (Huntsville, Al), and is supported by a group of NASA mentors from different centers.

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GaLORE (Gaseous Lunar Oxygen from Regolith Electrolysis): Recent Technology Advances for a Cold-Walled Molten Regolith Electrolysis Reactor.

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On the lunar surface, production of commodities to support human presence, such as water, food and oxygen, and sustain the growth of a permanent outpost will likely require the use of local resources. The moon is covered almost entirely with fragmented oxide minerals known as regolith hundreds of meter thick. As a resource, it is rich in oxygen (> 42 wt.%) bound in a solid state with a variety of metals. The molten regolith electrolysis (MRE) reactor is a promising technology for the production of gaseous oxygen from the lunar regolith in a simple, single-step reaction that requires minimal consumable materials, produces oxygen and metals with high electrical efficiency and high yields from any regolith composition. This process involves melting regolith to ~1600°C then electrolyzing the molten pool to separate metal and oxygen ions that are then collected as liquid metal and gaseous oxygen at the respective electrodes. Lab-scale demonstrations of the MRE technology have previously relied on external heating sources to bring the entirety of the reactor up to the operating temperature which creates corrosive interfaces between the molten regolith and the containment material in the reactor, limiting the overall lifespan of a reactor [1]. The Gaseous Lunar Oxygen from Regolith Electrolysis (GaLORE) project is focused on the development of a "cold-walled" or "Joule-heated" reactor design in which an internal heating source is used to selectively melt a pool of regolith between the electrodes of the reactor, leaving a shell of solidified regolith between the molten pool and the containment vessel of the reactor. This next generation reactor concept has been under development as molten oxide electrolysis (MOE) by MIT and Boston Metal for the production of iron from pure ores for terrestrial application [2]. The GaLORE project is engaged in early development of the technology for use with varying lunar regolith compositions in the lunar environment.

Thermal modeling of a proposed cold-walled reactor design were used as a scaffold to develop parameters for a feasible reactor shape and size as well as target energy consumption [3]. The current development effort for the cold-walled reactor design will be presented as an experimental study of the most promising techniques for melting regolith within the constraints imposed by the lunar environment. Heater devices are designed to accommodate limited electrical power availability on the moon, a wide range of regolith compositions that may be seen on the moon, limited metals available for replacing consumed parts, and the low thermal conductivity of granular regolith in vacuum. In addition, designs for the integration of heater devices into a reactor to transition into the electrolysis phase of the reaction are presented.

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Loop Heat Pipe With 3D Printed Evaporator Designed for the NASA VIPER Engineering Demonstration Unit. R. Gupta[1], C-H. Chen[1], and W. G. Anderson[1], [1]Advanced Cooling Technologies, Inc., 1046 New Holland Ave, Lancaster, PA 17601 (Contact: rohit.gupta@1-act.com)

Abstract: A Loop Heat Pipe (LHP) featuring a 3D printed evaporator was designed and fabricated by Advanced Cooling Technologies, Inc. (ACT) as part of the engineering demonstration unit for NASA's Volatiles Investigating Polar Exploration Rover (VIPER). The LHP formed part of ACT's thermal management solution for the NIRVSS and MSolo spectrometers. The 3D printed evaporator was developed by ACT as part of a separate NASA-funded SBIR program aimed at minimizing the manufacturing costs and lead times of evaporators by eliminating the labor-intensive processes. With 3D printing, the entire evaporator was printed as a single, continuous part complete with such components as the primary wick, the vapor grooves and the outer solid wall. A CAD rendering of the evaporator cross-section and a photograph are presented in Figure 1. The evaporator featured a 316L stainless steel construction with a length of 4-in and a diameter of 1-in. With an intensive parameter development effort, the primary wick capillary limit was maximized to an equivalent pore radius of under 8 μm at bubble point. The details on the wick capillary development can be found in a recent publication by this abstract's authors[1]. CAD renderings and photographs of the full LHP is shown in Figure 2. The LHP also featured a Thermal Control Valve (TCV), highlighted in Figure 2. The TCV was incorporated to allow for the vapor to bypass the condenser below a desired temperature. The LHP was tested successfully to the desired power level in the ACT testing facility. Given the success in meeting a set of mission-specific requirements, the current effort serves as a demonstration of significant technological progress in additively-manufactured advanced heat transfer devices.

References:

[1] Gupta, R., Chen, C-H., Anderson, W., "Progress on 3D Printed Loop Heat Pipes," 50th International Conference on Environmental Systems, 2021.

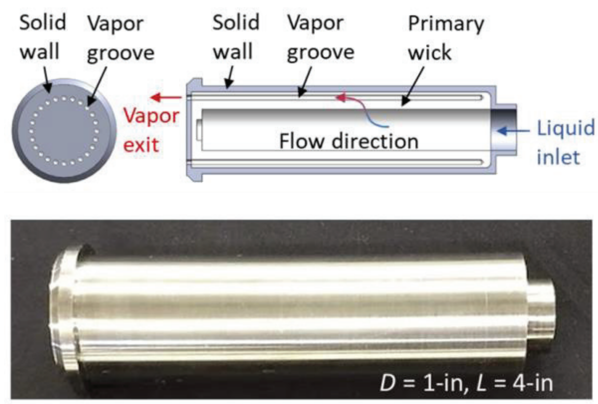

Figure 1. (top) CAD rendering of the 3D printed evaporator, and (bottom) a photograph of the 3D printed evaporator.

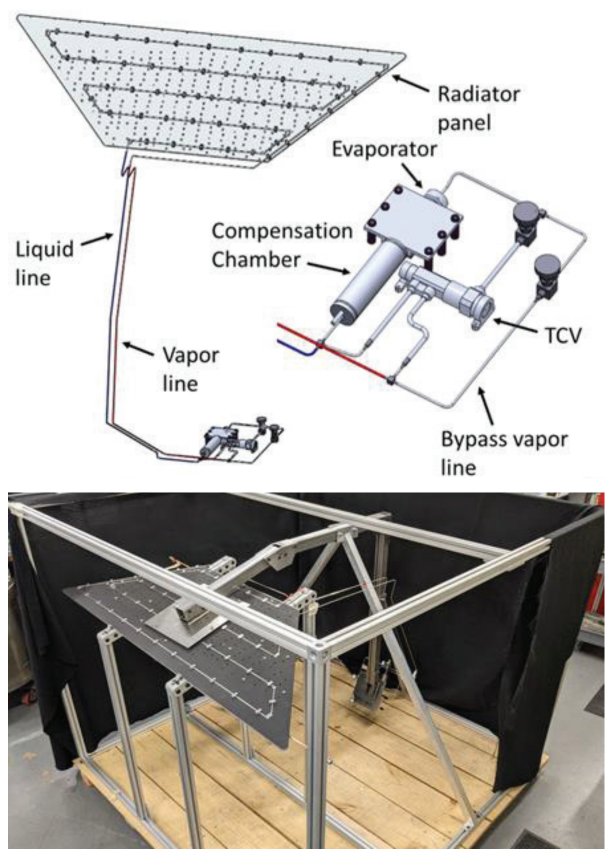

Figure 2. (top) CAD rendering of the LHP, and (bottom) a photograph of the LHP in the shipping rack.

Macro Triboelectric Stair-Stepped Behavior of Dipole Dust: Harnessing Surface Power High Voltage Dust. D. Hawk, United First Nations Planetary Defense, W11575 W Town Hall Rd., Gresham, WI 54128. (Contact: itspaceagency@gmail.com/678.702.7180)

Introduction: Lunar Dust is a well-known primary exploration limiting factor i.e., Apollo 11 dust characterization, Apollo 12 Dust Detector Experiment (DDE) leading to LEAM and LADEE LDEX, and Chang'e-3 Yutu. Lunar nanophase iron dust harbors magnetic and electrical charge properties.

Dust Bowl, dust storms, were highly charged electrical storms with potentials into the hundreds of kilovolts known to cause lightning, knocking people unconscious, deaths occurred. Abrasion concomitant dipole dust particles arcing across the positive cornea and negative retina caused cattle and people to go blind. Dipole-dust lofted in optimum concentrations produce one hundred kilovolts plus charged clouds arranged in a 3-axis negative-positive geopotential array [1]. Like volcanic eruption dust lightning, large landers are expected to produce high velocity triboelectrostatic buildup of electrons accumulating on the spherical dust dipole ends and may be enough to create lunar cloud lightning upon landing and takeoff.

High voltage rocket engine dust plumes will be 3-axis checkerboarded, 1/6-G geopotential-ridged, negative-positive clouds of charged spherical dipole particles. The clouds will be 45-degree stair-stepped. Dust Bowl storms reached heights of 13,000 feet reported by aircraft and carried by the jet stream with known sand deposition on decks of ships three hundred miles in the Atlantic. On the Moon, some dust will be jettisoned off the surface and into orbit while the rest of the dust will be carried across the entire lunar surface.

Lunar Equipment: In addition to sand blasting, surface equipment exposed to rocket engine dust cloud ejecta will be impacted by 3-axis checkerboarded waves of electrically charged negative and positive clouds with the highest electrical potential closest to ejecta dust optimum concentration-to-charge potential. In addition to rocket engine caused lightning, charged triboelectric dust arcing will impact most lunar surface electronic equipment and optics such as a WPT laser lens.

Conclusion: The bad news first. In addition to rocket engine sand blasting, in waves lunar equipment and astronauts will be exposed to high voltage dust potentials into the 100s of kilovolts. The good news is, if lunar dust is optimally lofted in negative and positive clouds it could produce vast amounts of lunar surface power.

Figure 1. Dust Bowl dust storm.

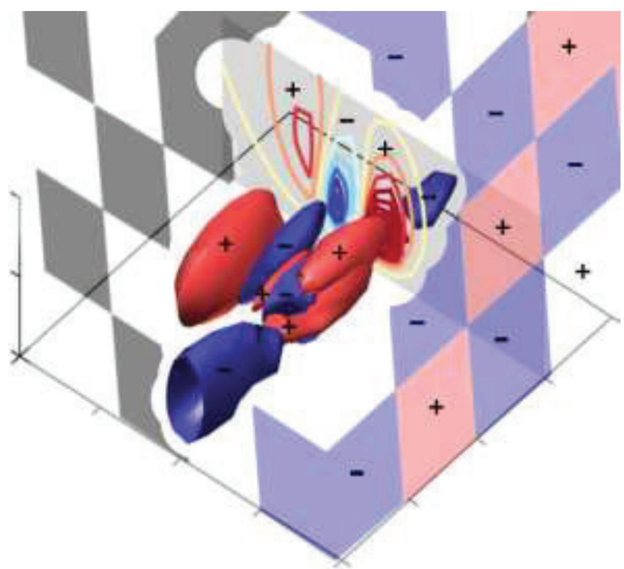

Figure 2. Overlay of 3-Axis Electrical Cloud Construction of a Reconstructed Electrical Dust Storm from Locally Observed Electric Field Data [1].

References: [1] Zhang, H., Zhou, YH. Reconstructing the electrical structure of dust storms from locally observed electric field data. *Nat Commun* **11,** 5072 (2020).

New Capabilities in Lunar Surface Environment Testing at MSFC. E. Hayward[1], T. Schneider[1], J. Vaughn[1], P. Lynn[1], M. Nehls[1], [1]NASA/Marshall Space Flight Center, EM41, Huntsville, AL. (Contact: erin.g.hayward@nasa.gov)

Introduction: Planetary, Lunar, and Asteroid Natural Environment Testbed (PLANET) is a new, state-of-the-art, combined space environments laboratory facility currently being built and outfitted at NASA's Marshall Space Flight Center. A major challenge of developing and infusing new technologies into exploration systems is finding a laboratory platform that provides comprehensive high-fidelity space and surface environments to reduce risk and guarantee performance; PLANET is designed to help meet that need.

PLANET is being built around a 2x3 meter customized vacuum chamber with specialized port arrangements allowing for a maximized combined environments test envelope. PLANET is designed to provide the following environments:

- Charged particle radiation (electron and proton)
- Low density plasma, high vacuum (10^{-7} Torr), or planetary atmosphere
- Thermal extremes (liquid nitrogen cryogenic system; heaters)
- Ultraviolet radiation (including high-energy vacuum UV)
- Large regolith simulant bed (lunar or Martian).

These environments can be applied simultaneously, allowing for high-fidelty study of synergistic effects, or alone, for basic research into damage mechanisms. Types of tests that are enabled by this suite of equipment include spacecraft charging studies, thermal/optical property change measurements, mechanical/material properties degredation investigations, and regolith mechanical wear, adherance, and removal tests.

We will discuss planning, development, and the current status of this capability, which is expected to be fully online and available for customer use in early 2024.

Overview of NASA's RESOURCE (Resource Exploration and Science of OUR Cosmic Environment) Project.

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Executive Summary: The RESOURCE (Resource Exploration and Science of OUR Cosmic Environment) project is supported by NASA's SSERVI (Solar System Exploration Research Virtual Institute) and is led by Principal Investigator (PI) Dr. Jennifer L. Heldmann and Deputy PIs Dr. Matthew Deans and Dr. Alexander Sehlke at NASA Ames Research Center. RESOURCE is focused on enabling In Situ Resource Utilization (ISRU) near the sites of robotic and/or human missions to enable sustainable and affordable exploration of the Moon and near-Earth objects (NEOs). This year RESOURCE has supported the development of a summary of the current state of knowledge regarding lunar polar volatiles as well as a comprehensive catalog and analysis of NEOs. RESOURCE is developing advanced mission capabilities to enable rapid, collaborative operations for lunar resource exploration missions. Hardware testing has been conducted to evaluate potential contaminants released during lunar polar regolith heating. Volatiles and particulates are the two sources of contamination that will affect the requirements of a water cleanup system, and RESOURCE research has identified the requirement for filtration prior to electrolysis for ISRU. RESOURCE also supports development of next-generation planetary drilling systems with integrated instrumentation within the drill. RESOURCE is also deeply committed to sustained efforts to engage educators, students, and broadening participation among underrepresented groups, and has partnered with Howard University in Washington, DC to foster minoritized students' interest in STEAMD (science, technology, engineering, arts, math, design) careers through direct and virtual experiences with NASA Subject Matter Experts.

Resource Characterizations: Using our current understanding of the processes that contribute to the distribution of water in lunar PSRs (Permanently Shadowed Regions) and constraints from data on larger spatial scales, we devised multiple potential distributions of water ice as well as correlations with additional physical parameters such as surface roughness. Also, geostatistical analysis techniques across lunar datasets are being developed by leveraging established USGS capabilities to systematically evaluate resource potential.

Advanced Mission Operations Capabilities: The MIT team is developing a suite of virtual tools for data analysis and mission operations. The Virtual Mission Simulation System (vMSS) is a virtual reality platform currently under development and testing to determine integration and usability pathways for data display, collaborative analysis, and rapid decision making. Multiple instruments for data collection have also been field tested to provide science data as well as enable accurate 3D VR/AR/XR (virtual/augmented/mixed reality) renderings of an analog field site to capture surface features and physical forms.

ISRU Water Processing: Work supported by RESOURCE at the NASA Johnson Space Center (JSC) is working to process extracted water in an ISRU plant and demonstrate an integrated test of the critical components needed to capture, clean, deionize, and electrolyze water as well as dry the oxygen and hydrogen gas products.

Lunar Drilling Technologies: The RESOURCE team at Honeybee Robotics has been focused on developing advanced downhole technologies to integrate instruments (including neutron and near-infrared spectrometers, dielectric spectroscopy probe, temperature sensor & heater, and camera) into the drilling auger. This advancement changes the paradigm of planetary exploration: instead of bringing samples to an instrument we are bringing an instrument to the samples.

Public Engagement: The RESOURCE team is working to engage educators, students, and broadening participation among underrepresented groups. We have designed STEAMD resources to cultivate underrepresented students' interest in space science and aerospace careers.

Metal Manufacturing on Lunar Surface – from Alloys to Components

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Abstract: Keystone Synergistic Enterprises, LLC is a provider of large format metal additive manufacturing (AM), having extensive experience in metal working and materials analysis of aerospace alloys including subscale channel wall rocket nozzle AM for NASA MSFC and Wire Metal AM in-situ defect detection for NASA STMD. Keystone has been an active member of LSIC and aims to bridge the critical gaps of in-situ metal components manufacturing and metal feedstock supply for a sustainable lunar base infrastructure development. To fulfill these aims, Keystone plans to undertake a capability development of manufacturing metal components such as construction structural elements (metal beams, columns), construction vehicle components (metal hulls, trusses), weld wire and power transmission cables etc. – all based on lunar surface-based resources. To develop the groundwork for this, Keystone will team up with QuesTek Innovations LLC and perform extensive study and analysis to narrow down feasible metal alloys to be derived from lunar regolith, followed by AM parts production.

QuesTek Innovations is a recognized global leader in Integrated Computational Materials Engineering (ICME) technologies and has the expertise and resources to efficiently create new materials meeting mission-specific properties. QuesTek uses its proprietary Materials by Design® methodology to rapidly design, test, characterize, qualify and insert new high-performance materials into industrial use. To address the materials needs in LSIC's ISRU and E&C endeavors, QuesTek proposes the following – (1) a wide range of existing earth-based construction alloys (steels, aluminum-, titanium-alloys, etc.) will be surveyed and assessed to identify potential manufacturability on the lunar surface using resources extracted from lunar regolith. Information regarding composition and microstructure of lunar regolith provided by the ISRU team will be utilized. And (2) new lunar-based materials and processes may need to be designed/developed in order to achieve optimized materials performance when manufactured using lunar regolith. QuesTek will leverage its expertise in understanding and modeling materials' key process-structure-property (PSP) relationships to design and develop novel materials compositions and processes, that are tailored to be manufactured from the specific lunar regolith resources.

Keystone proposes to use this database of relevant alloys and the PSP relationships and ultimately derive wire feedstock (collaborating with ISRU and wire supplier partners) which will be used for further manufacturing the necessary lunar base infrastructure elements using arc and laser wire metal AM processes. The reason for using wire is for easier feedstock management and safety compared to powder. Keystone currently houses two robotic Wire Arc metal AM cells and planning to establish an in-house Laser Wire metal AM cell. These in-situ defect detection and identification-capable AM cells will be used for earth-based demonstrations and developing early stage coupon and component build testing. The Wire Arc system is used for high deposition rate, large parts AM, and the Laser Wire system is used for smaller parts AM, channel wall heat exchangers' closeout deposition and additively performing near net finishing of the Wire Arc AM parts. A roadmap will be prepared for evolving the technologies for lunar environment considering lower gravity, vacuum, wide temperature swing, low weight, low energy, high autonomy and in-situ defect repair requirements. Collaboration is planned to include manufacturers of lunar construction vehicles to address vehicle component manufacturing on the moon. Overall, Keystone envisions to synergistically develop a lunar resource-based metal manufacturing facility contributing to a sustainable lunar base establishment.

Fig 1. (Top-Left & Bottom) Large metal components manufactured by Keystone using in-house robotic Wire Arc Metal AM cell. (Top-Right) Channel wall nozzle closed out using Laser Wire AM.

An Area-Based Management Approach for Regulating Lunar Mining Activities.

K.M. Hubbard[1*] and L.T. Elkins-Tanton[1]. [1]Arizona State University, 781 Terrace Mall. Tempe, AZ 85281. (k.m.h@asu.edu)[*]

Introduction: The development of lunar mineral resources is hindered by two major factors: 1) the absence of an institution and instrument for issuing long term exclusive rights to explore and exploit the Moon for its resources and 2) a process by which a title could be acquired to explore and exploit an area and claim its resources. We recommend governance of Lunar mining activities using Area-Based Management Instruments. Such instruments are conventionally used in spatial planning and management of particular areas on Earth to regulate the distribution, timing, and intensity of activities. Moreover, they require a designated authority to implement and oversee rules, regulations, and procedures in specified areas requiring higher protection or restrictions [1]. A Lunar Spatial Planning Tool (Figure 1) is currently in development to facilitate the implementation of such instruments on the Moon.

A case study was conducted on the International Seabed Authority's (ISA) management of seabed minerals to identify best policies and practices for implementation in Area-Based Management of lunar mineral resources. The case study includes analysis of the ISA's 1) historical development and negotiating history, 2) guiding principles, 3) its 'Mining Code' [3], and 4) its Environmental Management Plan for the Clarion Clipperton Fracture Zone.

The Lack of a Lunar Governance Regime: We recommend the development of a Lunar Resource Management Authority (LRMA), an international regime responsible for: i) encouraging the development of lunar resources, ii) developing and administering area-based management strategies, iii) safeguarding the lunar environment as it may be affected by mining activities, and iv) ensuring the equitable use and economic benefits of lunar mineral resources.

Regulations, Policies, and Procedures: We recommended the following for overseeing Lunar mining activities: 1) a notification process for prospecting, where a lunar contractor must notify the LRMA of its intention to engage in prospecting, 2) an application process in the form of contracts where the LRMA would issue exclusive but temporary rights to a contractor to explore and exploit an area on the Moon's surface, providing security of tenure, 3) a Parallel System of Reserved Areas. This equitable management strategy reserves mining areas for non-space faring nations, which are partitioned from each contract area granted to a Lunar contractor, 4) a "Relinquishment" procedure, both for resolving overlapping claims and for a contractor to delineate Reserved Areas, 5) the development and use of Areas of Particular Scientific Interest, which will implement Preservation Reference Areas and Impact Reference Zones to safeguard the lunar environment, 6) the development and use of Areas of Particular Operational Interest, which prohibit mining activities in areas due with high significance to another sector, and 7) the incorporation of priorirty rights and first possession principles (i.e., Homesteading) [4] for the "Pioneer Investors" that invest in the early development of lunar mineral resources.

The Lunar Spatial Planning Tool: The Lunar Spatial Planning Tool tool divides a lunar resource system into a grid of mining blocks. By simplifying the lunar surface into blocks, the tool facilitates the recognition of rights and compliance and enforcement of the recommended rules, regulations, and procedures listed above.

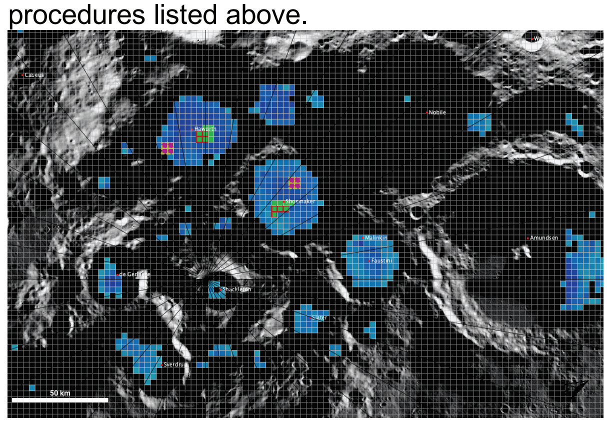

Figure 1 - Example of the Lunar Spatial Planning Tool dividing the south polar region to 80ºS into ~9km^2 mining blocks. Colored blocks indicate locations with an average maximum summer temperature of <101K [5], which was used as a proxy to delineate locations potentially suitable for prospecting for lunar ice deposits. Pink blocks are hypothetical Areas of Particular Scientific Interest reserved for environmental impact studies and other scientific purposes. Green blocks are two hypothetical contract areas to explore for lunar ice deposits. Green blocks outlined in red depict "Reserved Areas" partitioned out of the contract areas by the lunar contractors that will be reserved for future mining entities from developing States.

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Lunar Shyn. Michael Ilsbroux, Epic Blue, Asstraat 5 3000 Leuven, Belgium, michael.ilsbroux@epic.blue

Introduction: Lunar exploration and human long term sustainment present many challenges identified by the LSIC community. One of these challenges is working in extreme environments and operational access to locations on the Moon. This abstract briefly introduces the context of navigation. Then, it discusses how certain technologies developed for Earth use can be the basis for the Lunar environment.

Extreme Access: How to enable humans and robotic systems to efficiently access, navigate, and explore various lunar surface and subsurface areas with minimal infrastructure?

The extreme Lunar environment offers challenges in positioning (PNT) and wayfinding for both people and robotic systems. The following elements impact positioning:

- No localisation infrastructure
- Lack of magnetic field
- Craters
- Volcanic features, lava tubes
- Areas of high and low (shadow) Illumination

Several projects are being designed for beacon-based navigation. Creating a specific Lunar GPS is a solution far down the line. The LuGRE project plans to use the GPS signals from earth-orbiting satellites for Lunar-based positioning. The ESA LCNS looks at a comprehensive system of satellites and beacons for PNT. Positioning based on radio antennas similar to cell phone positioning or relying on long-range beacons like LORA and Ultra Wide Band are also considered. The Moon has a nearby horizon which adds to the challenge.

Lidar is also being investigated as positioning technology. Part of the research is to understand the impact of dust on these sensors.

As these systems take shape, there will be a period of human and robotic presence preceding such positioning systems. However, even with such systems in place, positioning faces the same challenges as Earth GPS when moving in tunnels, in deep canyons or craters, etc.

In light of this, it makes operational sense to have a reliable, lightweight PNT solution that, in the short term, can operate autonomously and which can gradually add the features of GPS or beacon PNT capabilities in the mid to long term.

Earth Shyn: Shyn is a wearable Epic Blue solution for seamless positioning in GNSS and GNSS-denied environments. Shyn takes a novel Artificial Intelligence based-approach to positioning. Shyn exploits IMU (inertial measurement) data to ensure continuous positioning using a known location as a starting point. Shyn can also rely on beacons and GPS to determine starting points or intermediate reference points. https://vimeo.com/502116641

Lunar Shyn: Epic Blue proposes to exploit PNT technologies already developed and validated on Earth and apply them to the Lunar environment and missions. With this concept, the astronaut suit has a Shyn-like device embedded. As astronauts leave the base or other reference locations (e.g. the position of a rover), Shyn is given an initial position fix and starts tracking its wearer's movements. Shyn incorporates different movement models, including scope usage of ladders, ascents and descents, fall/impact detection and alerting. In a pre-Lunar GNSS stage, positioning and heading are based on Shyn inertial and any signals from prepositioned beacons. As more initiatives for Lunar GNSS come to fruition, Shyn evolves to a recipient of those signals, effectively becoming an advanced 'GNSS tracker', similar to its role on Earth. Several use cases can be covered with this concept:

Use Case 1 - Lunar Caves & Tunnels

Use Case 2 - Astronaut Operations

Use Case 3 - Human-Machine Collaboration

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Earth to Lunar: Transposing the technology from Earth application to the Lunar environment requires a stepwise experimental and validation multi-layered approach. Next to roadmap evolutions the following are key experiments to have:

- Device Environmental Suitability
- Device Component Suitability
- AI Model Suitability

NASA Regenerative Fuel Cell Development Status Update. I.J. Jakupca[1] , P.J. Smith[2], K.P. Cain[2] [1]Fuel Cell Technology Lead, National Aeronautics and Space Administration (NASA), Glenn Research Center (GRC), 21000 Brookpark Road, Cleveland, OH 44135, [2]Photovoltaic and Electrochemical Systems Branch, NASA GRC, (Contact: ian.j.jakupca@nasa.gov)

The specific energies (W·hr/kg) of currently available energy storage technologies impose unacceptable mass penalties on lunar missions, especially systems designed to support a persistent human lunar surface presence during the lunar night. The National Aeronautics and Space Administration (NASA) funds research into multiple technologies to minimize this mass penalty and satisfy as many mission requirements as possible. This includes the electrochemical regenerative fuel cell (RFC) technology based on the hydrogen (H_2) / oxygen (O_2) couple.

This presentation provides a summary into the status of the RFC project funded by the Space Technologies Mission Directorate (STMD) Game Changing Development (GCD) program office. The RFC project is tasked to advance the RFC energy storage technology from a Technology Readiness Level (TRL) 3 to TRL 5 by designing, developing, and demonstrating via ground-test, a subscale (100 W_{Net} / 36.6 kW·hr_{Net}) automated RFC system within a thermal-vacuum (TVAC) facility that simulates the temperature and pressure environment of an equatorial lunar landing site. This system design must be extensible to a full scale system of 7 kW_{Net} / 2.6 MW·hr_{Net}. Minimum success criteria requires that the system fully supports the external load profile(s) throughout the simulated lunar nights within the thermal-vacuum chamber, illustrate a specific energy of at least 320 W•hr/kg, and complete at least one full lunar day-night cycle within the thermal-vacuum chamber. For reference, the state-of-the-art (SOA) packaged Li-ion battery systems have a specific energy of approximately 160 W•hr/kg (576 kJ/kg) at the time of this publication.

While developing the ground-test system, the RFC project identifies technology gaps that must be addressed to implement this technology on the lunar or Mars surfaces. Ongoing efforts reveal a range of technology gaps with a wide distribution of difficulties to address these gaps. Select component gaps discussed include sensors, pumps, water purifiers, power electronics, storage tanks, electrochemical stacks, passive humidification control devices and safety devices. The system-level technology gaps identify insufficient test data on life, durability, and reliability at both the component and sub-system levels. This data gap increases technical risks associated with system design and packaging.

The RFC project continues to assess developing technologies for viability and potential inclusion into the RFC demonstration system. Alternative compression technologies, water sanitization technologies, and thermal management technologies are examples of near-term technologies being assessed. Long-term system assessments include alternative reactant combinations, multiple system integration within a habitat, and requirement sensitivity to landing site locations.

Presentation Title: Digital Engineering a Lunar Rover

Authors: Dr. Steven Dam, Mallory Jones, Michael Jordan, Lilleigh Stevie, Andy Tapia

Format Type: Slideshow (.PPTX)

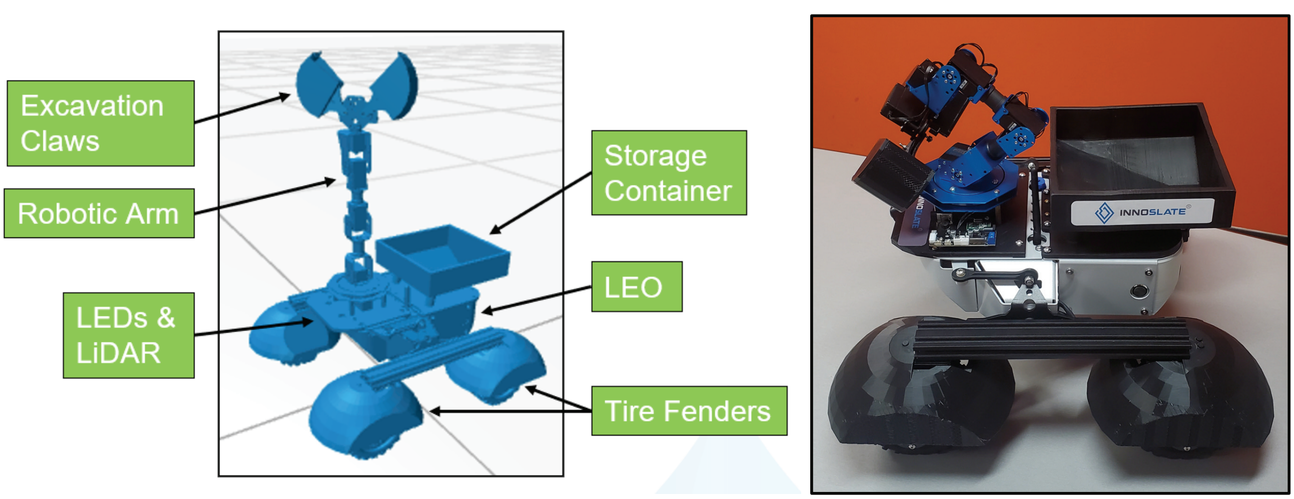
Description:

As part of NASA's Break the Ice Challenge Phase I, a lunar rover system architecture was designed to excavate icy regolith and extract water for creating a sustainable source of water on the surface of the Moon.

This project utilized the end-to-end digital engineering and MBSE tool, Innoslate, to research and design, build, and test a lunar rover prototype. Requirements in Innoslate's Documents View were written to define the rover system's functionality, as well as, to specify the extreme lunar environmental conditions and specific performance parameters that must be adhered to. Action diagrams were created to model and simulate the lunar mission to determine how long the proposed lunar rover system will take to collect 10,000 kg of water on the lunar surface. Finally, Innoslate's Test Center was beneficial in recording tests conducted in the lab and in the field to verify and validate the lunar rover prototype. Further analyses were also conducted using Innoslate's various integrations with other tools such as STK, MATLAB, and Ansys. Having a well-integrated systems and design engineering environment reduced prototype development time and cost significantly throughout the project.

This digital engineering project produced a fully functioning lunar rover prototype with sub-systems that drive and navigate the rover on the lunar surface, excavate icy regolith, store and protect collected materials such as water and regolith, and power the rover for at least 365 days.

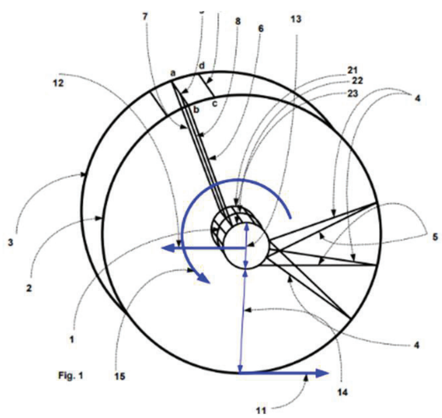
The figure below is SPECTER, a Space Prospecting Excavator Convoy Transporting & Evaluating Regolith.



A performance analysis concluded SPECTER, scaled up to the size of an Appollo mission rover, is able to excavate 250,000 kg of 4% concentration regolith to be converted into 10,000 kg of water in 10.67 months with a total energy consumption of 4,800,556 mAh.

Two Low Cost Lunar Cargoes (2LCLC): OPLONAS and MACEDONAS. Charis KOSMAS. Author[1], [1]Lunar Cargo P.C., 19 El. Venizelou Ave., 16343 Ilioupolis, Greece, mailing address. (Contact: charis.kosmas@georing.biz)

Introduction: two Low cost lunar cargoes (2LCLC) takes advantage of the special morphology of the lunar surface (namely flat planes and crater rims) for delivering large cargo (**OPLONAS**) and regular parcels (**MACEDONAS**) respectively, through mechanical means, in the place of the "classical" chemical propulsion. An important aspect in both systems is that they also take advantage of the fact that there is no atmosphere around the Moon and so no trajectory perturbations due to atmospheric effects. Additionally the construction of MACEDONAS can be made possible by scavenging the material from OPLONAS. The savings which can be achieved are in the range of 70%, considering that currently all lunar landing vehicles have a net of 30% of the total



mass of the orbiting vehicle, the rest being fuel and associated thruster and structure mass .

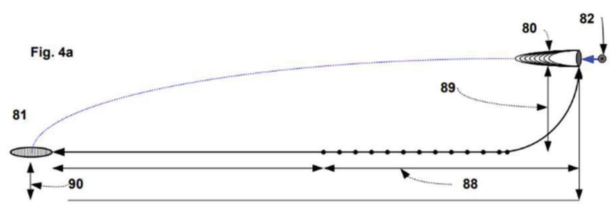
OPLONAS: (Oversized Payload Lander On Non-Atmospheric Somata) The spacecraft named OPLONAS is a 60 meters diameter wheel shaped spacecraft, consisting of a rigid, payload-containing cylindrical core of of 6 meters diameter and 6* Φ height and a flexible part which is deployed through spin motion, right before touching the lunar surface. With a rotational speed of 8.62 revolutions/sec the spacecraft will not suffer catastrophic impact upon contact with surface but it will roll and bounce for several 100's kilometres till it will dissipate all kinetic energy and eventually fall to rest. Important characteristic of the flexible part of OPLONAS is its construction by means of ZYLON® ropes, which is the only known commercially available material, capable of sustaining the enormous tension generated by the centrifuge forces, which will develop by the high rotational speed.

OPLONAS Characteristics

Minimal to no fuel needs. Can negotiate obstacles of up to 27 meters). Scale potential and evolvable.

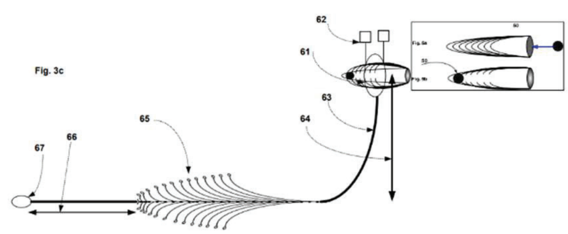
Mode of operation:

The core spacecraft is launched with the flexible part wrapped around. Uppon arrival to low lunar orbit (LLO) spacecraft spins up and deployes the wheel sole protetor of perimeter $2*(6*\Phi)^2$. Lands on a flat lunar surface (example Mare Imbrium), and dumps kinetic energy by roll friction along a long corridor. It makes available through scavenging, flexible elements material for making up MACEDONAS structures.



MACEDONAS: (Momentum Absorption Catcher for Express Deliveries On Non-Atmospheric Somata) MACEDONAS consists of a catcher, a central tether and a dendritic system designed to decelerate smoothly a parcel that may hit the catcher.

Operating Principle.



The **catcher** is an apparatus which resemples the batterfly catcher but having multiple (embedded) layers of nets chich can all but the last one be perforated by the parcel.

The **Core wire,** attached to the rim of the catcher, engages mechanically and follows the ballistic trajectory of the parcel.

The **dendritic system**, consisting of successive wire segments, which are engaged one by one, (as the catcher continues to fly) and decelerates parcel to zero velocity before it falls to rest on a safety net.

Unlocking the Value of the Moon with New, Innovative Solutions. Matthew Kuhns, Vice President of Research and Development at Maten Space Systems, 1570 Sabovich St, Mojave, CA, 93501 (Contact: mkuhns@masten.aero)

Introduction: The Moon offers a tremendous amount of value for humans right here on Earth. The first samples brought back from the Moon during the Apollo era changed the way we thought about the solar system, the history of Earth, and our place in the universe, and there's still so much science to uncover. From an environmental perspective, the Moon offers an abundance of resources, such as water, oxygen, and rare-Earth metals, that can be used to produce fuel, support manufacturing needs, and unlock new commercial applications. And from an economic standpoint, the global space market is expected to exceed $1 trillion and drive millions of high-paying jobs.

The Moon is also the gateway to our solar system. It has a harsh environment that we have to solve for before we can explore further into the solar system.

So how do we unlock the value of the Moon and beyond? We must find solutions to mitigate hazardous lunar dust, survive the cold lunar night, navigate the lunar surface, and utilize lunar resources. Masten Space Systems is playing a key role in building new, innovative technologies to solve these pressing challenges and unlock the value in space for humans on Earth.

Mitigating Lunar Dust: Razor-sharp regolith caused by robotic and human landers is a major challenge for the future of space exploration. This dust can damage landers, payloads, surrounding infrastructure, and even pose a hazard to astronauts. Masten is solving this challenge with an in-Flight Alumina Spray Technique (FAST) that creates instant landing pads by injecting ceramic particles into a rocket engine nozzle and building up a coating over the regolith prior to landing. This approach minimizes harmful dust particles and enables more landing locations for complex lunar, Mars, or asteroid missions.

Following a Phase 1 NASA Innovative Advanced Concepts (NIAC) award, Masten spent the last year studying and advancing the FAST concept in collaboration with Honeybee Robotics, Texas A&M University, and the University of Central Florida. Masten can share the latest data from our research that proves the solution is feasible in the lunar environment.

Surviving the Lunar Night: Temperatures on the Moon can reach as low as low as -232°C (or -387°F) during the lunar night, causing spacecraft systems, rovers, and payloads to fail. Masten's Nighttime Integrated Thermal and Electricity (NITE) System solves this challenge by delivering heat and power through the oxidation of metals using propellant margin from the lander's propulsion system. The NITE System autonomously operates when temperatures fall below a specified threshold, enabling landers and payloads to extend mission operations for at least 12 months.

Masten is on track to finalize the NITE heat generation subsystem by mid-2022 following a NASA SBIR Phase II award and can share the latest test results.

Navigating the Lunar Surface: Unlike Earth, the Moon isn't equipped with GPS so lunar spacecraft and assets are essentially operating in the dark. Masten's lunar position, navigation, and timing (PNT) solution proposes to fix that with surface-based sensors that can be deployed from a spacecraft into a dedicated sensor array on the Moon. With functionality similar to GPS, the autonomous network can enable navigation and location tracking for spacecraft, assets, and future astronauts on the lunar surface or in lunar orbit.

Masten is currently developing the network prototype following a Phase II SBIR contract through the Air Force Research Laboratory's AFWERX program. The PNT technology will soon be tested aboard Masten's rocket-powered lander, Xodiac, to demonstrate payload integration and beacon operations in a terrestrial environment, enabling a path towards lunar demonstration.

Extracting Lunar Ice: Usable as drinking water, rocket fuel, and other vital resources, lunar ice is critical to maintain a sustained presence on the Moon and allow future missions to Mars and beyond. Masten's Rocket Mining System can autonomously extract more than 420,000 kg of water per year. It uses a series of rocket plumes under a pressurized dome to fluidize ice particles and a vacuum-like system to store the water. The full system can be attached to a rover and delivered via Masten's lunar landers.

The Rocket Mining System was recently selected as one of the winners of NASA's Break the Ice challenge. Masten aims to continue developing the full system in 2022.

BORONITE®
Extraordinary Materials for a Demanding World

Lightweight Robust Power Cables for the Lunar Surface

David Lashmore* Ph.D., CEO, American Boronite Corporation (David.lashmore@boronite.com)
Professor Lourdes Salamanca-Riba Ph.D. University of Maryland (riba@umd.edu)

ABSTRACT

We can, (1) fabricate carbon nanotube (CNT)-copper and CNT-aluminum composite cables capable of carrying hundreds of amps, (2) we suggest the development of a low-cost mass production “method” for CNT cables, and (3) as background we have demonstrated fabrication, insulation and connectorizing a large 2 AWG gauge cable for testing of conductivity, specific conductivity, and fatigue.

For this cable we were able to demonstrate sustained currents of *167* amps and transient currents to over *550* amps, all measured by an outside company. We were not able to reach the fusing current. This cable was repeatedly folded on itself with almost no radius of curvature without damage, an achievement beyond carbon fiber or even copper cables. This older cable was made of CNT braided copper alloy wire each braid with specific conductivity 3605 Sm^2/kg and a conductivity of 10.5 MS/m. Since this older submission, we have been able to increase the specific conductivity to over 12,639 Sm^2/kg and (2) overall conductivity to 15.2 MS/m. At this level even very lightweight data-coaxial cables cores can be made using the proposed SuperWire™ braid as a core conductor. Our proposal goal of achieving higher than 14,000 Sm^2/kg for a 50% CNT-metal cable now seems in reach.

We feel that our proprietary wetting processes will have a big effect on transport in these hybrid cables. We posit that better understanding of electron transport with atomic resolution TEM microscopy of the metal interface and of the composition gradients will enable us to finally exceed 14,000 Sm^2/kg specific conductivity with a goal of 25 mS/m or more depending on density and on the metal-alloy we use. To achieve higher density, we will use in situ compression techniques. We feel that the key to conductivity is the nature of the interface, purity of the material, and density. We propose that by conducting high resolution transmission electron microscopy-TEM, that we will gain insight on the nucleation process of the alloy on the CNT graphene surfaces. We will conduct in house conductivity according to Mil Spec and conduct temperature vs current curves, determine fatigue (wire test) characteristics, conductivity following folding tests and measure conductivity at 60 Hz and at 400 Hz. We have developed an advanced CNT yarn spinning system with compatibility with our in-house braider and show how this system can economically produce high power cables as well as coaxial cables. The steps are
Illustrated in the Figure Below:

Manufacturing Steps for fabricating a metal/ CNT composite Cable: (1) produce the yarn in a CVD reactor, (2) braid the yarn on a 16 bobbin raider, (3) heat treat the braid to form A copper-alloy/CNT composite, (4) gather enough braids to carry the needed current and (5) insulate and add connectors big enough to carry the design current, the figure shows a four foot long cable.

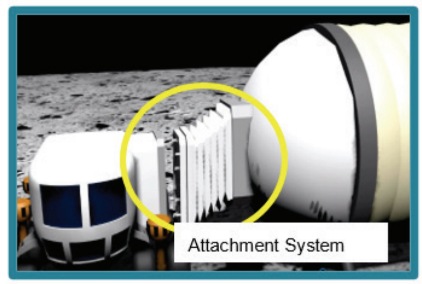
The Standardization of In-space and Surface Docking Systems J. L. Lewis and S. R. Donahoe, NASA Johnson Space Center, Structural Engineering Division, Mailcode ES, 2101 NASA Parkway, Houston, TX 77058 (Primary Contact: james.l.lewis@nasa.gov)

Introduction: The International Docking System Standard (IDSS) aids on-orbit crew rescue and joint operations between different spacecraft. For the International Space Station (ISS), the IDSS has enabled Global interoperability for Commercial Crew and soon JAXA, and the standard is currently being extended to the Artemis Program missions. As more companies, agencies, and nations announce their intentions to explore and occupy low Earth Orbit (LEO), Cis-Lunar space, including the Lunar surface, it is a natural extension that new standards will be developed to support infrastructure build-up for mission-based or permanent occupation and exploration by national and multi-national Agencies, Industries, and Companies.

Image: Space X Commerical Crew Docking System (photo from internet)

A surface version of the IDSS, a.k.a. IDSS-Surface (IDSS-S), is under consideration by the NASA docking discipline leads responsible for the leadership of technical development and negotiation of the original IDSS a little over a decade ago. The IDSS-S, like its predecessor, will detail the physical geometric mating interface and design load requirements to ensure physical interoperability and support a broad set of design reference missions. An IDSS-S, if used, increases the probability of successful Lunar surface docking between different modules enabling the accessibility and inclusivity required for multi-national, sustainable Lunar exploration.

While this paper will not delve much into the background of the development of the IDSS, the experience of developing, implementing, and managing the IDSS as a standard offers valuable insight and lessons learned applicable for creation of a IDSS-S as future Lunar surface element providers pursue development of the modules, systems, and infrastructure required to be assembled and/or connected to enable a permanent sustainable Lunar capability.



Concept depecting Rover and Lunar Surface Module Docking. Docking Adapter concept utilizing the future Standardized Interface and Pressurized Tunnel to overcome misalignment.

NASA JSC Docking designers have on-going activities exploring surface docking and shirt sleeve transfer capabilities which include articulating systems and inflatable tunnels to perform the docking and transfer functions between two elements. A primary objective is to explore and document the features and requirements of a potential international interface standard with the goal this year to create a draft of the new surface standard and begin dialog with commercial and international counterparts heading towards baselining in a few years. Keeping schedule is important in order to be able to support anticipated and ongoing architectural, ground-based, and flight development activities leading towards a future sustained lunar surface operations; including the potential to scar early Artemis elements/vehicles for potential retrofit of a docking interface or by on-ramping this/these capabilities later as they mature.

Efforts are currently underway by the Structural Engineering Division at the NASA JSC seeking substantial active partnering with Industry with the expectation to accelerate work in this area to the benefit of enabling lunar surface sustainability faster, fewer impacts, and decreased overall cost.

Experimental Considerations for Ground-based Testing of Lunar Construction Technologies. J. Long-Fox[1], K. Dudzinski[2,3], R. Mueller[2], L. Sibille[2,4], E. Smith[2], E. Bell[2], J. Gleeson[2], B. Kemmerer[2], J. Fothergill[2], M. Effinger[5], R. L. McCormick[6], D. Newell-Smith[6], S. Moreland[6], L. Hipskind[6], E. Marteau[6] P. Abel[7] [1]University of Central Florida, 4111 Libra Drive Rm 430, Orlando, FL 32816, [2]Swamp Works, NASA Kennedy Space Center, Merritt Island, FL 32899, [3]University of Houston, 4800 Calhoun Rd, Houston, TX 77004, [4]Southeastern Universities Research Association (SURA), Washington D.C., [5]NASA Marshall Space Flight Center, Huntsville, AL 35812, [6]Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA 91109, [7]NASA Glenn Research Center, 21000 Brookpark Rd., Cleveland, OH 44135. (Contact: jared.long-fox@ucf.edu)

Introduction: The Moon-to-Mars Planetary Autonomous Construction Technology (MMPACT) project, under NASA's Game Changing Development (GCD) Program aims to research, develop, and demonstrate lunar surface construction capabilities [1]. Lunar infrastructure development requires quantifying the geotechnical properties of lunar regolith, such as shear strength, compression properties, and angle of repose. Knowledge of geotechnical properties enables prediction of forces and displacements associated with lunar infrastructure development processes including excavation and constructing landing pads, habitats, shelters, and roadways. Ground-based testing of relevant hardware (e.g., robotic arms) in appropriate lunar regolith simulants enables validation of technology choices and tool paths to develop autonomous lunar systems. Such testing also generates data to give insight into the regolith properties on the lunar surface.

Design of Experiments (DoE): Data from in-lab testing of lunar hardware ground interactions can serve as a reference to inform on the geotechnical properties of lunar regolith. Geotechnical studies are concerned with normal and shear loads, so experiments that involve compressive and shear forces should be emphasized. These include pressure-sinkage, shearing, excavation, and induced slope failure.

A resource-efficient DoE created using Taguchi methods [2] minimizes the number of experiments needed to explore the parameter space of the input factors and the goal is to design robust experiments that are informative in uncontrolled conditions [2]. A factorial DoE tests every combination of input factors [3], but available resources do not always allow for the extensive experimentation it requires. Combinations of Taguchi and factorial DoE are being investigated for MMPACT and other lunar missions to maximize the knowledge gained from laboratory testing of lunar construction hardware and to better constrain geotechnical properties.

Geotechnical Data Analysis: Pressure-sinkage experiments provide information on the bearing strength and stiffness of regolith [4] and are directly relevant to lunar construction efforts. Key parameters are the Mohr-Coulomb shear strength parameters of cohesion and angle of internal friction, which can be estimated by slope failure [5] and shearing experiments [6] which also allow estimation of sliding strength (adhesion and angle of external friction) [7]. Excavation forces depend on depth, gravity, and physical properties of the regolith being manipulated [8]. Geotechnical data analysis and force prediction techniques range from analytical models that generally assume simple planar geometries [8] to geometrically-flexible numerical methods such as finite element models (FEMs) [9] and discrete element models (DEMs) [10].

Conclusions: Quantifying the geotechnical properties of lunar regolith is key to lunar infrastructure development efforts, as improper ground-based testing and site characterization puts personnel, hardware, and emplaced infrastructure at risk. Proper testing of regolith-tool interactions in a controlled laboratory setting generates data for comparison to lunar surface data enabling prediction and modeling of forces observed during lunar surface operations.

References:

[1] Clinton R. G. et al. (2021) DOI:10.2514/6.2021-4072. [2] Taguchi G. (1987) *Methods to Optimize Quality and Minimize Costs*. [3] Hicks (1964) *Fundamental Concepts in the Design of Experiments*. [4] Rashidi et al. (2015), DOI:10.5829/idosi.aerj.2015.42.48. [5] Marteau et al. (2021) *LPSC 2021* Abstract #2067. [6] Nayar et al. (2019) DOI:10.1177/1729881419885696. [7] Goshtab et al. (2009) *Proc. CIGR Int. Sympos. Australian Soc. Eng. In Agric.and Biosys.* [8] Wilkinson A. and DeGennaro A. (2007), DOI:10.1016/j.terra.2006.09.001. [9] Zhang et al. (2018), DOI:10.1016/j.still.2017.12.011. [10] Jiang et al. (2017), DOI:10.1016/j.jterra.2017.01.002.

Photonic Extension Cords – Directed Energy for Lunar Power Distribution

P. Lubin, P, Meinhold, P. Srinivasan, N. Rupert, A. N. Cohen, B. Phillips
Physics Department, University of California Santa Barbara, CA, USA. (Contact: lubin@ucsb.edu)

Introduction: In order to sustain extended operations on the lunar surface, a scalable method of power distribution is required. As part of our NASA-supported power beaming program, we propose the development of directed energy (DE) power distribution systems capable of transmitting power across kilometer-scale distances for difficult-to-reach and mobile applications on the Moon. Such applications include beaming power from crater rims into permanently shadowed regions (PSR) where large deposits of water have been shown to exist (illustrated in Figure 1), as well as beaming power from stationary sites to mobile assets such as rovers and other surface vehicles. The system we propose is effectively a "photonic extension cord" which beams near-infrared laser light to distant assets, at which it is converted via tuned high-efficiency photovoltaics (PV) into useful electricity. Such DE systems are now efficient, low-mass, practical, cost-effective, and continue to rapidly improve due to exponential growth in photonics which is driven by vast consumer and industry demand. [1] A wide range of other applications can be enabled by a scalable DE power distribution system: tower-to-tower "photonics power lines" with distances exceeding 100km and power levels exceeding 10kW; lunar surface-to-orbit or orbit-to-surface power beaming; and ultra-high speed laser communications for all of the above configurations. Even longer ranges and higher powers are possible with coherent combining of single mode lasers.

Current Labwork: We have designed, built, and tested 1064nm Yb fiber high-power single mode systems with 43% (emitter, from 50% pump efficiency and 85% conversion) wall plug efficiency pumped at 976nm in our lab. Including PV conversion efficiencies, end-to-end efficiencies of ~20% is currently possible, with 25-30% appearing feasible in the modest future. Our group has worked for 10 years developing the technology to allow extremely long range power projection, and we have already built lab-scale power beaming demonstrations up to 120W (optical) with both Si and InGaAs/metamorphic PV devices at wavelengths of 808, 880, 976, and 1064nm.

Periscope Beam Director. We have developed a demonstration laser power beaming and tracking system capable of near-4π FOV steering and active target tracking. It is compact (<30cm cube), low mass (5kg including laser), highly capable with optical power output of up to 400W, with extension to >1kW, and can operate in either single or multi-mode. If multi-mode, a 10cm aperture can project an ~80cm diameter spot at 1km distance, and a similar unit with a 1m aperture operating in single-mode could be used to project power at 100km range with a sub-meter diameter spot.

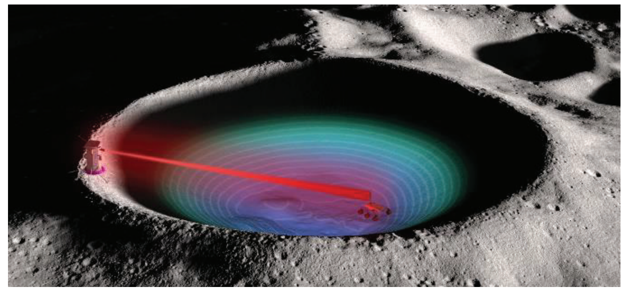


Figure 1: Example of power beaming from a lunar lander (Intuitive Machines Nova-C shown) to a rover within a PSR. Shackleton Crater is shown, with a depth of 4.2km and width of 21km. We can provide power across the entire diameter, if necessary.

Laser-Tuned PV. We have built laser PV converters in our lab using Si and InGaAs (Spectrolab) cells including novel low mass compact high speed (10kHz) maximum power point tracking (MPPT) electronics, which allows maximizing power in time-varying conditions.

Thermal Energy Capture & Storage. In addition to electrical power, the photon energy not converted to electrical energy can be harvested as thermal energy, which is critical in many applications, including operating at low temperatures during the lunar night or in PSR's. Properly done, capturing and storing this energy can greatly increase the overall efficiency of the system.

Future Goals: We intend to further develop all of the above sub-systems in order to perform power beaming demonstrations at power levels relevant for lunar operations. This will include optical beacons on the transmit/receive sides for pointing, wide and narrow FOV visible/NIR imaging, and optical + RF communications. We are working on Si and InGaAs PV arrays capable of 0.1-1kW electrical output in a lab demonstrator system that has the essential functionality required for outdoor testing and lunar operation.

References:

[1] P. Lubin (2016) *arXiv:1604.01356.*

Towards Novel Nonprehensile Conveyance of Lunar Regolith via Surface Traveling Waves

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Introduction: Most ISRU architectures envision robots handing lunar regolith from the extraction zone and transporting it from the mining site to the processing. Then at the processing end, the bulk-material conveyance system transports regolith between different stages of processing and eventually carries out the reacted regolith from the reactors. These processes require transporting raw material, final product, and reacted by-products. As a result, there is a need to develop infrastructure to transport and process lunar regolith. Mechanical conveyors with rotating augers and pneumatic systems are the two traditional methods.; There are significant challenges in building the infrastructure on the lunar surface for either of these options. Mechanical conveyors with rotating parts have to overcome large frictional forces and thus require substantial power and are susceptible to jamming and wear, increasing human intervention and a need for maintenance.

On the other hand, a closed-loop pneumatic system relies on compressed gas, a valuable commodity in space, and its recovery is vital for lunar applications. Electrostatics, presence of bends, high power requirement, pipe erosion, choking phenomenon are some of the issues present with pneumatic systems. Although these are tested for microgravity environments, other material conveyance mechanisms such as vibratory conveyors are yet under- or un-tested for lunar applications.

Vibratory conveyors are often easy to maintain, take different form factors, and work at high temperatures. However, they traditionally rely on bulky motor/actuators with rotary parts as well as the presence of gravity, which can prove challenging for low gravity applications. We propose the use of surface traveling waves to transport material as an alternative to these methods. This method has many advantages . With minimal design modifications, one can convert any platform/surface into a material conveyor. Distributed surface actuation with piezoceramics or macro fiber composites (MFCs) is sufficient to generate surface waves that transport material. Such a design provides the much-needed flexibility of designing conveyors that are easy to maintain. Figure 1 conceptually visualizes the role of surface traveling waves in conveying anf segregating lunar regolith.

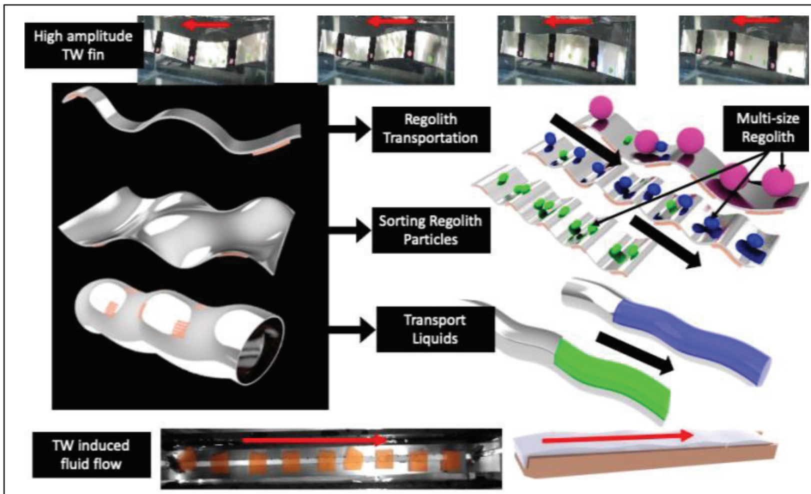


Figure 1: Conceptual illustration of using traveling waves for regolith transportation and segregation

Furthermore, this method can also be extended to pump fluid in micro-gravity.

The current work investigates how steady-state traveling waves are developed in finite structures and identifies the factors that influence steady-state wave characteristics. Theoretical and experimental analysis is conducted on 1D and 2D designs to realize the different traveling waves. Owing to the robust attributes of the piezoceramics (PZTs) in vibrational studies, we developed piezo-coupled structures to develop traveling waves through experiments.

In this presentation, we will discuss the process of generating steady-state traveling waves on any surface using the two-mode excitation method developed by our research group. In particular, we highlight some of our preliminary outcomes of conveying material and pumping fluids using these traveling waves.

ISRU 3D Printing of High Solid Suspensions for Off-Earth Construction. A. E. Marnot[1] and B. K. Brettmann[1,2], [1]School of Chemical and Biomolecular Engineering, Georgia Institute of Technology, 901 Atlantic Dr. NW, Atlanta GA, 30332, [2]School of Materials Science and Engineering, Georgia Institute of Technology, 901 Atlantic Dr. NW, Atlanta GA, 30332. (Contact: amarnot3@gatech.edu)

Introduction: With the upcoming return to the Moon and crewed missions to Mars in preparation, additive manufacturing techniques are becoming more prevalent within the construction space. In contrast to the processing difficulties that hinder the use traditional AM methods in low-temperature, low-gravity, and low-atmospheric environments, direct-ink-write (DIW) offers unique solutions to these challenges. When used to process locally-derived resources, DIW can facilitate the construction of operating bases on other planetary bodies through reduced waste, improved safety, and lower payload and transportation costs. However, formulation factors and their effect on extrudability, solidification and shape-retention are typically not well understood when the suspension is processed in an extreme environment. Here, we utilize a model particle system to stand in as regolith and assess the use of a polymeric binder for AM-enabled construction with insitu resource utilization. An assessment of the rheology gives us insights into the printability of the suspensions as well as their shape fidelity. Our polymeric binder allows us to explore the potential of UV-cure to solidify dense suspensions and leverage lower costs and simpler operations for construction at low temperatures. We analyze the effects of particle loading, binder formulation and temperature on the achievable depth of cure, and utilize this method to set our printing parameters, showing successful prints with particles loadings up to 70 vol%. Through the deconvoluted characterization of these suspensions into both the extrusion and curing processes, we show that we can expand the range of printing materials and introduce cost-effective candidate binder formulations for off-Earth construction.

FLEX: Flexible Logistics & Exploration Rover. J. B. Matthews[1], [1]Venturi Astrolab, Inc., 12536 Chadron Ave Hawthorne, CA 90250 (Contact: jaret@astrolab.space)

Introduction: NASA and private industry investments will soon make it possible to land unprecedented amounts of cargo on the Moon at a regular cadence. Venturi Astrolab, Inc. (Astrolab) is developing the multi-functional Flexible Logistics & Exploration (FLEX) rover with this burgeoning environment in mind (Figure 1). The FLEX rover's unique commercial potential comes from its novel mobility system architecture, which gives it the ability to pick up and deposit modular payloads in support of human operations, robotic science, exploration, logistics, infrastructure deployment, site survey/preparation, construction, maintenance, & repair, resource utilization, and other activities critical to a sustained presence on the Moon and beyond.

Figure 1: The FLEX rover is an LTV-class mobility platform with adaptive utility enabled by modular payloads

Adaptive Utility: FLEX is a Lunar Terrain Vehicle (LTV)-class rover that can carry two suited astronauts and all their associated equipment, tools, instruments, and samples. FLEX features a novel wheel-on-limb mobility system that can raise and lower the ground clearance of the chassis and adapt to variable terrain while maintaining stability. This system also allows the rover to lower attached instruments and equipment to the ground and/or independently collect and deploy modular payloads. FLEX can accommodate payloads with volumes in excess of $3m^3$ and masses of up to 1,500 kg.

Astrolab has developed a full-scale, fully-functional terrestrial proof-of-concept FLEX rover and recently conducted field testing at an analog site in the California desert. At these field trials, FLEX was used to conduct demonstrations of various activities and operational scenarios that will be required on the Lunar surface [1]. These included the transport of crew and their EVA equipment, deployment of a Vertical Solar Array Tower, and the semi-autonomous transport and deployment of various types of cargo (Figure 2).

Figure 2: FLEX's modular payload interface and novel mobility system enable it to perform a multitude of functions, including (left to right, top to bottom): outpost logistics, crew exploration and science, infrastructure deployment, robotic science, and crew rescue tasks

Open Payload Interface Standards: Astrolab recently published a Payload Interface Guide to educate potential partners and customers on the capabilities of FLEX and the various ways it can accommodate payloads. Astrolab is now inviting government, academic, and commercial entities to partner with us in the design and field testing of payload concepts. We seek to foster a community of payload developers adhering to an open and standardized interface. We believe this will ultimately lead to a vibrant Lunar economy, in much the same way that intermodal standardized payload containers have become the lifeblood of trade on Earth. The use of standardized payload interfaces is critical for diverse participation on the International Space Station, and the approach that Astrolab is advancing will be similarly vital for a sustained human presence on the Moon.

[1] NASA HEOMD-006: Human Exploration Operations & Utilization Plan (2021)

Motion Control Technologies for the Sustainment of Lunar Exploration. T. M. McCarthy[1], [1]Motiv Space Systems, 350 North Halstead Street, Pasadena, CA 91107. (Tom.McCarthy@motivss.com)

Introduction: NASA has stimulated the movement toward a sustainable presence on the Lunar surface through the CLPS program, technology investment programs, HLS selections, developing technology roadmaps for power generation and deploying ISRU technologies to support human presence.

Motiv realizes one of the greatest challenges in accomplishing the goals of sustained presence on the moon involves the survivability and robustness of the assets to be delivered to the surface. The lunar day/night cycle delivers some of the harshest environmental conditions our planetary spacecraft and systems can experience. Daytime temperatures can exceed 120°C and nighttime teperatures in certain regions can drop below -180°C. These challenges are in addition to the classic lunar dust issues and make operations for robots and equipment difficult to exceed lfetimes beyond a single lunar day.

Motiv has utilized the NASA SBIR program to help develop it s own technology roadmap which allows for avionic motion control systems and actuation systems to not only survive but operate throughout the lunar night without thermal accommodation. Essentially, take the environments head on, as-is, and perform.

This paper will explore the contributions of the DACEE (Dual Axis Controller for Extreeme Environments) and its deployment on the COLDArm mission slated for a 2024 CLPS launch as a technology demonstration with JPL. In addition, the DEEDS (Distributed Extreme Environments Drive System), as funded by the SBIR Phase II Sequential Program, is a next generation modular control and high power actuation system designed to meet the needs of the future lunar robotic systems, mobility platforms, cargo offload equipment, and a variety of processing equipment which will be relied upon to operate continuously for years, not weeks.

LuNA – System Model for Lunar Healthcare Delivery. O'Neil, D.A.[1] and Hasnain, S[1], [1]Johns Hopkins University - Applied Physics Lab, 11000 Johns Hopkins Road, Laurel, MD 20723. (Contact: daniel.oneil@jhuapl.edu)

Introduction: Our goal is to create a notional healthcare system model as a prototype for national healthcare delivery and individual health

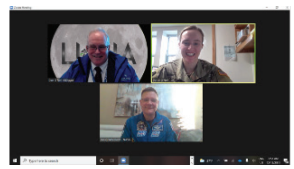
The poster presents results from a Hackathonat Johns Hopkins Applied Physics Lab, Sessions were sponsored by the Janney Innovation program and included Multi-Viewpoint Conceptual Modeling (MVCM), a simulation process design session and development of an interactive game to study the system model for Lunar Healthcare Delivery

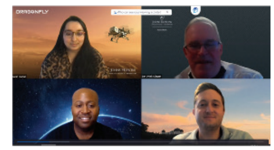
MVCM is designed to bridge different stakeholder perspectives by providing multiple viewpoints into all aspects of the conceptual model.

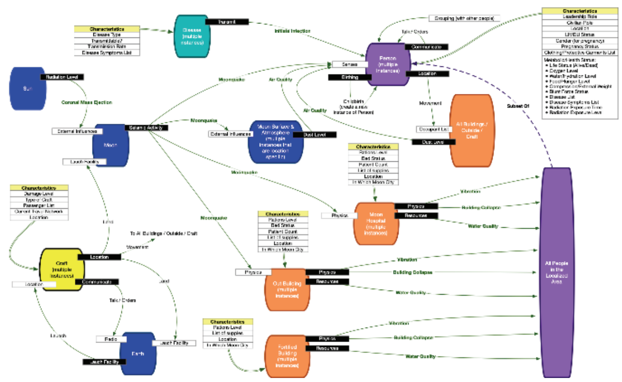
The output of the sessions was developed and distributed open source. Components included the conceptual model, a simulation framework, and a human-in-the-loop game for efforts requiring alignment and integration of multiple, complex systems

References:

[1] Katherine L. Morse. and David L. Drake Multiviewpoint Conceptual Models 2019. [2] Mock, Sherrel W or Robinson, David A. Nato Modeling Center of Excellence 2021.







Coupling Microwave Energy to Lunar Regolith With Near-Field Coupling Device. Q. H. Otte[1] and A. J. King[1], [1]Radiance Technologies, 310 Bob Heath Dr., Huntsville, AL 35806. (Contact: Quinn.Otte@radiancetechnologies.com)

Introduction: Toxic and abrasive, lunar regolith creates hazards for a long-term human presence on the moon. Simultaneously, long-term habitat features such as vertical structures and pavement require delivery of materials to the moon. Both problems can be solved by consuming local regolith at the habitat site to build rigid materials through sintering. High-power microwaves are a promising heat source to perform this sintering, but efficiently and effectively sintering using radiative transmission has proven difficult without embedding susceptor materials in regolith simulants. Leveraging near-field effects rather than radiative effects promises improve microwave heating in lunar regolith without adding susceptors.

Concept: Previous attempts to heat lunar regolith to sintering temperatures have focused on using antennas to radiate microwaves into the lunar surface. However, material characterization of regolith simulants suggests that the simulants, and likely the regolith itself, has a relatively low dielectric constant and a small loss tangent [1][2]. Using an antenna placed just above the surface will heat the top surface through near-field coupling, but will also have significant radiative loss, depositing much of the microwave energy deep below the surface.

Alternative devices, like waveguides, that do not have significant radiative loss can enhance energy transfer to the target volume of the regolith. The device instead incorporates the regolith as its dielectric medium. For waveguides placed on top of their dielectric medium, coplanar waveguides are often preferred to slotlines due to the ease of feeding this structure. However, the single-gap geometry of slotlines focuses their electric fields in that gap, making slotlines more desirable for this application.

Design: To design a proof-of-concept device for heating regolith simulant, a simple long slotline was chosen. The primary design parameters are the frequency of radiation, the width of the slot, the length of the slotline, and the feed type. The frequency and slot width, along with material properties, determine the depth of electric field penetration. The slot width and material properties determine the characteristic impedance of the slotline and combine with the slotline length and feed type to determine the device input impedance.

Slotlines can been used as slot antennas when they are a half-wavelength long at the operating frequency and shorted at the end. Because this is not the desired operation of the device, the slotline was chosen to be several wavelengths long so that most of the energy propagating along the slotline will be lost to the target regolith before it reaches the end and reflects. This approach also reduces lobing in the heating patterns due to interference between waves traveling opposite directions. This choice also reduces the impact of the shorted end of the slotlines on the primary heating volume.

Slotlines are often fed with microstrips in a manner that relies on a wavelength-dependent, and therefore narrowband, impedance matching technique [3]. A Dyson balun was chosen to feed this slotline device to give a wider-bandwidth match that can more easily be used with varied material properties for different regolith simulants or variations in regolith properties in different regions of the lunar surface [4].

Performance: The near-field device was built out of copper, an aluminum frame, and a copper coaxial cable. Using a $1\ \mathrm{kW}$ continuous-wave amplifier and an $800\ \mathrm{MHz}$ input signal, the device heated a central node of approximately $100\ cm^3$ volume by $16°\ \mathrm{C}$ in 15 minutes, with other nodes of heating to lesser degrees within the simulant bed.

Future Work: The next step for this device concept is to demonstrate regolith sintering using waveguide materials that will maintain their shape at sintering temperatures. A steel slotline with a high-temperature coaxial cable have been assembled and are ready for testing.

Once sintering is achieved, the slotline can be shaped to deliver microwave energy more efficiently for heating strategies for both paving applications and additive manufacturing applications.

References: [1] Prabhu V.L. et al. (2018) *Microwave Heating of Lunar Simulants JSC-1A and NU-LHT-3M.* [2] Barmatz M. et al. (2011) *Microwave Permittivity and Permeability Measurements on Lunar Simulants*. [3] E. M. et al. (1969) *IEEE Transactions on Microwave Theory and Techniques*, *17*, 1091-1096. [4] J. D. (1959) *IRE Transactions on Antennas and Propagation*, *7*, 181-187.

Permittivity Testing of Lunar Regolith Simulants Using Small Sample Sizes. Q. H. Otte[1] and A. J. King[1], [1]Radiance Technologies, 310 Bob Heath Dr., Huntsville, AL 35806. (Contact: Quinn.Otte@radiancetechnologies.com)

Introduction: Proper characterization of both lunar regolith and simulants in terms of their dielectric properties is essential to evaluating and developing hardware and processes that will succeed in sintering regolith on the moon. There is an existing body of work characterizing the dielectric properties of regolith, conducted from 1972-1978 [1] [2] [3] [4] [5]. Several features of this existing data make it insufficient for sintering process research. Many studies suffer from lower sample rates and do not examine permittivity variation over frequency ranges, instead focusing on a handful of discrete frequencies which are below the frequency range useful for sintering. Furthermore, due to the logistical complexities of testing Apollor lunar regolith samples here on earth, a custom, advanced permittivity testbed is required to collect appropriate dielectric data.

Concept: The coaxial perittivity testing device is examined as an electrical 2-port network. The procedure uses a 2-port vector network analyzer (VNA) to measure forward and reflected power to and from each end of the device, obtaining the four scattering parameters (S-parameters) of the network. Since the simulants are non-magnetic, permeability is assumed $\mu_r^* = 1$, and complex permittivity is calculated from measured S-parameters. From the complex permittivity, loss tangent can be calculated. The test software utilizes time-domain gating and multi-step calibration to filter non-specimen effects on the signal.

Design: The testbed was designed to satisfy several objectives to allow testing of Apollo regoloth samples. Traditional measurement techniques, such as focused-beam or TEM cell measurements, all fail to comply with one or more of these design parameters. First, sample size must be minimized, due to the low regolith availability. Additionally, the testing must be nondestructive and the sample completely recoverable, *i.e.* the device must be easily cleaned. The device must operate within $0.5 - 15\ \mathrm{GHz}$ to span the range of potential sintering frequencies. Data must be gathered with a resolution of at least $20\ \mathrm{MHz}$. The device must function in a vacuum, due to regolith handling and storage requirements. Finally, a variable and measureable packing rate of the sample material must be accounted for.

The final design consists of a body that bisects into two equal parts, with a removeable center conductor. The coaxial terminals on each end of the device are APC7 standard. A Teflon plug keeps the center conductor in place during assembly and retains the sample during testing. The cavity is $7\ \mathrm{mm}$ in diameter, requiring less than $\frac{1}{2} cm^3$ of material.

Performance: The system is calibrated using a Maury 2650CK30 calibration kit and the empty, assembled device. The device is held in a test tube stand, with the cavity oriented vertically and the Teflon window at the bottom. A weighed aliquot of material is added into the cavity from the top of the device, and the packing density can be obtained by measuring the height of the sample via tamping rod insertion depth. Mating surfaces for the cables are cleaned using lint-free swabs. Then the cables are connected and measurements are taken. Data is collected using Copper Mountain's C1420 VNA and S4VNA software and processed using a custom software developed by Compass Technology Group specifically for this device.

This system is intended to be used at a constant temperature of $25°\ \mathrm{C} \pm 15°\ \mathrm{C}$. Varying temperature will invalidate the calibration. It is compatible with varied atmospheres, including argon, nitrogen, and vacuum.

The device has been used to measure the complex permittivity of the simulants JSC-1A, NU-LHT-4M, and synthetic anorthite. In the case on JSC-1A, measured values of real permittivity matched existing published data [6]. No existing published data is available for the other simulant materials.

Future Work: Further process development to allow gloved handling in a vacuum box is necessary. Alternative window materials may be tested to simplify calibration procedures. Once the device is validated in vacuum using simulant, a proposal for Apollo regolith sample testing will be initiated.

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THERMAL PROPERTIES AND MICROSTRUCTURE OF REMELTED LUNAR REGOLITH SIMULANT (OPRL2NT). Anis Parsapoor and Alan Whittington[1], [1]Department of Earth and Planetary Sciences, The University of Texas at San Antonio, One UTSA Circle, San Antonio TX 78249, Email: anis.parsapoor@utsa.edu

Introduction: Surface-based exploration of the Moon will require the construction of landing and launch pads to mitigate dust hazards, and of robust habitats to protect lunarnauts from temperature extremes and micrometeorite hazards. Because of the limited supply of lunar regolith on the Earth, analog materials (simulants) of lunar regolith are required as they allow more comprehensive studies [1].
Texture and grain size play a dominant role in controlling mechanical properties; therefore, knowledge of crystal nucleation and growth rates is important when optimizing the conditions of melting and cooling rate of molten regolith.

Methods and Materials: We focus on effects of different cooling rate on microstructural and thermal properties of a high-Ti mare lunar simulant, OPRL2NT. This consists of 10% anorthosite, 75.6% basalt, 14.4% ilmenite developed by Off Planet Research, LLC. The in situ differential scanning calorimetry (DSC) technique was used to investigate the solidification paths of OPRL2NT lunar mare simulant. Samples were heated to 1500 °C at 30 °C/min in PtRh pans under an Ar atmosphere, in a Netzsch DSC-404 F1 Pegasus. The samples were then cooled at different rates. The heat flow curves as a function of temperature were recorded three times for each experiment: first with an empty pan (baseline), second with a sapphire reference material (standard), and third with the sample under investigation. Data for the three curves can be combined using the Netzsch Proteus software to calculate apparent heat capacity for each cooling rate. Calorimetric measurements were combined with textural analysis conducted on basaltic melt cooled from liquidus to solidus conditions at rates of 10, 30, 40, 60, and 80 °C/min. The recovered run products were mounted in resin and polished for microscopic investigations.

Results: The heat capacity of OPRL2NT powder slowly increases from ~0.8 to ~1.0 $Jg^{-1}K^{-1}$, until the glass transition, with a maximum at about 670 ˚C ($T_{g,peak}$). This is followed by a trough in apparent heat capacity from ~750 ˚C to ~950 ˚C, extending to an apparent heat capacity of ~0.1 $Jg^{-1}K^{-1}$. The area of this trough corresponds to the enthalpy of crystallization of about -40 Jg^{-1}, where the negative sign indicates the exothermic nature of crystallization. The melting peak, beginning at ~1014 ˚C ($T_{m,onset}$), reaching a maximum at ~1163˚C ($T_{m,peak}$), with the heat capacity then falling and leveling off at ~1.1 $Jg^{-1}K^{-1}$ at ~1400 ˚C. The area under this peak represents the enthalpy of melting, about +407 Jg_{-1} in this case, where the positive sign indicates that melting is endothermic. For this experiment, 1440 ˚C marks the effective liquidus temperature (T_{liq}). During cooling of OPRL2NT from 1500˚C, heat capacity of the liquid is about 1.2 $Jg^{-1}K^{-1}$. When cooling at 30˚C/min, crystallization begins around 1200˚C and peaks at ~1078˚C and appears to cease at around 875˚C. The enthalpy of crystallization is ~105 J/g, suggesting about 25% crystallization. The glass transition begins at ~730˚C and is complete by ~670˚C.

Cooling rates play a crucial role in the microstructural evolution of textures, crystal size distributions and growth rates of crystallized minerals. To reveal the growth process and changing morphology of Fe-Ti crystals during the cooling experiments, we recovered the samples from the DSC, mounted them in resin and polished for microscopic investigations. At a cooling rate of 80 °C/min, a few patches suggest incipient crystallization, but no well-formed crystals were observed. At slower cooling rates of 60 and 40 °C/min, small feathery crystals were observed which may have nucleated heterogeneously on the PtRh pan. At cooling rates of 30 and 10 °C/min, acicular euhedral rutile and ilmenite crystals were clearly visible. These crystals are arranged in sub-parallel mats, which intersect the orientation of crystals in other mats at high angles. At a cooling rate of 10 °C/min, the crystals grew mainly via continuous growth, but above 30 °C/min, the main growth way was lateral growth and eventually forms a quadrilateral. When the cooling rate is fast, the viscosity of the melt increases quickly, inhibiting the diffusion of titanium [2]. This leads to rutile crystals being smaller at faster cooling rates. The sample crystallizes extensively when cooled at 30 and 10°C/min (ilmenite, rutile and glass), but only slightly at 40, 60 and 80°C/min. With decreasing cooling rate from 80 to 10 °C/min, the temperature of peak latent heat release increases from 822 to 1164°C, and the total enthalpy of crystallization increases from -17 to -105 J/g (Table 1).

Conclusion: For OPRL2NT, depending on the cooling rate, the major crystallizing phase were rutile and ilmenite. The molten simulant quenches to glass containing <5% crystals when cooled faster than 30 °C/min. At cooling rates of 10-30 ˚C/minute there is about 25% crystallization.

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Lunar ISRU Prospecting with BECA. A. M. Parsons[1], M. Ayllon Unzueta[1,2], and R. D. Starr[1,3], [1]NASA Goddard Space Flight Center, Greenbelt, MD, [2]Oak Ridge Associated Universities, Oak Ridge, TN , [3]Catholic University of America, Washington DC. (Contact: Ann.M.Parsons@nasa.gov)

Introduction: The Bulk Elemental Composition Analyzer (BECA) is a new instrument that has been matured through NASA's Development and Advancement of Lunar Instrumentation (DALI) program and has great potential for use in lunar In Situ Resource Utilization (ISRU) activities [1]. BECA employs nuclear techniques to measure the in situ near-surface bulk elemental composition on planetary bodies without the need to make physical contact with the surface. BECA's lunar ISRU capabilities are extensive with its ability to determine the elemental content of lunar regolith down to ~30 cm below the surface. BECA would thus be a valuable ISRU prospecting tool when placed on a rover where it could measure the lunar subsurface composition as the rover traverses the lunar surface. The resulting map of the locations and concentrations of key elements for ISRU would make the recovery of these resources much more efficient.

BECA Capabilities: Since BECA uses both gamma ray and neutron information, it can detect a significantly larger number of elements than available from instruments measuring only neutrons. BECA will measure hydrogen down to ~30 cm depth with gamma rays and down to ~60 cm depth with neutrons. Using the gamma ray and neutron information together, BECA may achieve H sensitivity at the100 ppm level allowing it to measure H abundances both inside and outside Permanently Shadowed Regions (PSRs). BECA will easily measure regolith oxygen content. Additionally, BECA will also be able to measure the regolith's Fe and Ti content thus allowing users to infer the presence of ilmenite ($FeTiO_3$) useful for oxygen extraction. BECA is also sensitive to carbon as well as the metals available in common lunar minerals. In fact, BECA can measure the concentrations of a wide variety of elements such as Al, Ca, Cl, Fe, O, K, Mg, Mn, Na, Si, U, Th, Ti and C.

Concept of Operations: As shown in Figure 1, BECA contains a Pulsed Neutron Generator (PNG) [2] that emits isotropic pulses of 14 MeV neutrons that irradiate the lunar regolith. Subsurface nuclear interactions in the lunar material produce gamma rays at energies characteristic of the isotopes that produced them. BECA's Gamma Ray Spectrometer (GRS) measures the energies and intensities of the gamma rays emitted by the lunar surface to determine the bulk elemental composition of the lunar regolith beneath the instrument.

BECA also includes Neutron Detectors (NDs) to measure rate and energy of the neutrons emitted from the surface to provide H and bulk property information. There are many advantages to having both GRS and NDs measuring the same volume of lunar regolith. The GRS detects a wide range of specific elements including H while the NDs measure H as well as bulk neutron transport properties of the regolith. Having two independent measurements of H improves sensitivity and reliability. Bulk regolith neutron transport properties measured by the NDs also provide a consistency check on the GRS results and the combination of gamma ray and neutron data should improve element depth inferences.

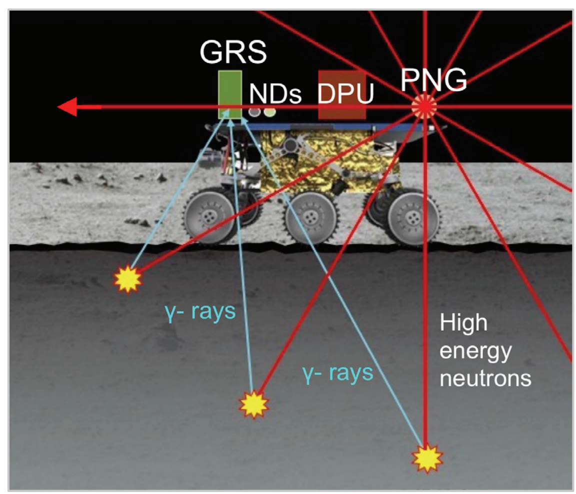

Figure 1: BECA can perform ISRU prospecting over the lunar surface.

Results: As a demonstration of BECA's lunar ISRU prospecting capabilities, we will present the experimental results of composition measurements of a monument of Columbia River basalt. This large (0.91m x 0.91m x 1.82 m) basalt sample has been independently chemically assayed and is located at a dedicated testing facility at NASA Goddard Space Flight Center (GSFC) [3].

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Assessing Impact of Joint Actuator Failure on Lunar Rover Mobility. C. A. Pavlov[1], A. Rogg[2] and A. M. Johnson[1], [1]Carnegie Mellon University, Department of Mechanical Engineering, 5000 Forbes Ave, Pittsburgh PA 15213. [2]KBRwyle, NASA Ames Research Center, Moffett Field, CA 94043. (Contact: catherinepavlov@gmail.com)

Figure 1. VIPER test rover at NASA Glenn Simulated Lunar Operations Laboratory, reproduced from [1].

Introduction: Wheeled rovers are critical to exploration of the lunar surface, and loss of mobility actuators can have mission-ending consequences. NASA's upcoming Volatiles Investigating Polar Exploration Rover (VIPER) has a four-wheeled active suspension, which gives it flexible extreme terrain mobility at the cost of an increased number of mobility actuators and potentially a higher mobility cost due to actuator loss than might occur on a similar six-wheeled rover [2]. We present both quantitative and qualitative assessments of rover mobility with multiple failure modes in the form of drawbar pull tests and motion-tracked driving. Preliminary analysis shows that mobility impact varies greatly by both the affected joint and its failure state, and that in some cases modification of driving strategy may be able to partially mitigate mobility impact.

Methods:

Data collection. All tests were conducted on a mock lunar rover with similar kinematics to the VIPER rover in GRC-1 lunar simulant [3]. 3D motion tracking was used to record the rover's position and orientation, and actuator speeds and positions were recorded for each suspension, steer, and drive motor. For drawbar pull testing, a fixed load was applied to the rover chassis via a tether to induce slippage, with tether load and length measured. Nominal driving performance with all actuators operational was measured with the same experimental setup as a mobility benchmark.

Failure modes. There are many potential failure modes for actuation of an active suspension; we consider a rover with four wheels, each of which has three actuators associated with it – one drive motor, one steering motor, and one suspension motor, for a total of 12 actuators. Each motor can potentially fail in a "stuck" (fixed orientation) state, as in the case of a rock jam [4], or "free rolling" state, such as in a power loss or actuator damage event. In addition, in the case of a stuck suspension or steering actuator the position at which an actuator fails can massively alter the mobility impact. A subset of potential failure modes were explored due to limited testing time, with a mixture of more operationally likely failure states and an attempt at representative coverage. The following failure states were tested individually: free-rolling drive actuator, stuck drive actuator, suspension locked with single wheel raised, and a single steer actuator locked at a fixed nonzero angle.The rover was driven both forwards and backwards for each free driving test, so that each failure mode was effectively tested on both a front and rear actuator.

Results: Loss of a drive actuator was associated with a high increase in slip, while steer and suspension actuators had a more moderate impact on mobility loss. In the most extreme case, a stuck drive actuator can result in the rover pivoting about the impacted wheel while making little forward progress. Steer actuator loss primarily impacts steering performance, while a stuck suspension can result in oscillatory behavior from the rover as it tips between the two support triangles formed by its wheels. Preliminary attempts at mitigating mobility reduction for different types of actuator loss were tried with underwhelming results, but gave insight into the future development of driving strategies.

Discussion: We have shown that actuator loss could be mission-ending for a four-wheeled rover such as VIPER, and mitigation strategies should be developed. Work on generation of driving strategies for actuator failure compensation through terramechanics modeling is in progress.

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Feasibility Study and Preliminary Design of Lunar Reconnaissance Drone. T. Pfeiffer[1], E. Uythoven[2], D. Rodríguez-Martínez[3], J-P. Kneib[4], and H. Koizumi[5], [1]Faculty of Mechanical Engineering, EPFL, thomas.pfeiffer@epfl.ch, [2]Faculty of Mechanical Engineering, EPFL, erik.uythoven@epfl.ch, [3]eSpace, EPFL, david.rodriguez@epfl.ch, [4]eSpace, EPFL for second author, jean-paul.kneib@epfl.ch, [5]Department of Aeronautics and Astronautics, University of Tokyo, hiro.koizumi@epfl.ch.
(Contact: david.rodriguez@epfl.ch)

Introduction: More than 50 years after humans first landed on the Moon, our neighbouring natural satellite has become the primary target of human exploration, scientific discovery, and commercialization in space for the upcoming decade.

The problem: With orbiting stations and ground bases planned to be built, we are yet to master the ability to explore long term and long range over areas of the Moon often characterised by an extreme topography, dauntingly low temperatures, and wedged with what are known as Permanently Shadowed Regions (PSRs). This represents significant challenges for traditional ground exploration approaches, often relying on individual, limited-range, slow, wheeled rovers. Precise knowledge about the terrain for an optimised route planning is crucial and often relies on limited-resolution satellite data from lunar orbiters, data that are even more limited in PSRs. The need for a long-range yet simple and lightweight scouting method is becoming more and more apparent.

Our solution: The goal of this project is to study the feasibility of a compact, lightweight, and versatile lunar reconnaissance drone that can be quickly deployed and refuelled from a ground vehicle or a rover. The drone will be capable of producing high-resolution maps (~10cm/px) that can be used to optimise mission planning and assist robotic assets on the ground. This innovative mission design was developed using established Systems Engineering tools and approaches. It highlights the main challenges of such a system and sets the baseline for future developments.

The main aspects defining the mission (i.e., propulsion, thermal, and mapping systems) have been addressed and analysed with reasonable assumptions. The study shows that a lightweight drone (15 to 20 kg) combined with a refuelling and recharging base on the rover is a promising concept.

The drone has an interchangeable payload in the form of a 3D mapping Lidar. Its propulsion uses 4 fixed green monopropellant thrusters. With one tank containing 1 kg of propellant (HPGP and He pressurant, for a total of ~5% of drone mass), a preliminary analysis shows the drone can complete a 1 km horizontal flight profile at 50 m AGL in about 10 minutes. A preliminary design of the drone's propulsion system is shown on Figure 1.

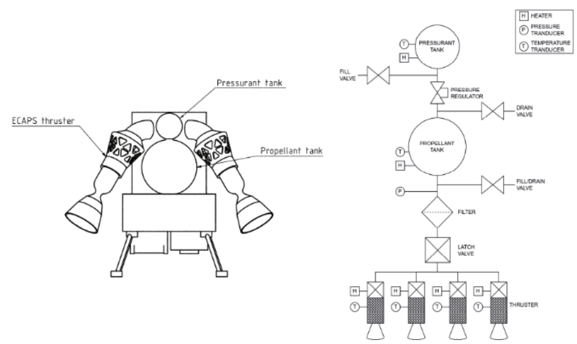


Figure 1: Preliminary design of the propulsion system of the drone allowing an unobstructed view of the ground from the payload.

The drone is refuelled and recharged on its base, which includes a take-off and landing (TOL) structure, a hold-down mechanism, a thermal and radiation protection cover, and the required electrical and data interfaces. A preliminary Concept of Operations (ConOps) is illustrated on Figure 2. At this stage, the results obtained suggest that the mission is feasible with currently or soon-to-be available technology.

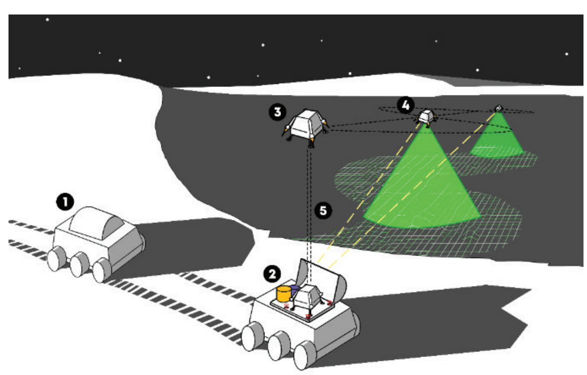


Figure 2: Illustration of the ConOps: 0. Launch and landing on the Moon (not shown); 1. Stand-by mode; 2. Flight preparation and deployment; 3. Take-off and vertical ascent; 4. Horizontal flight and mapping of the lunar surface; 5. Vertical descent and landing for data transmission, refuelling and standby.

Concept of Operations for the Establishment of Solar Drapes at the Lunar South Pole

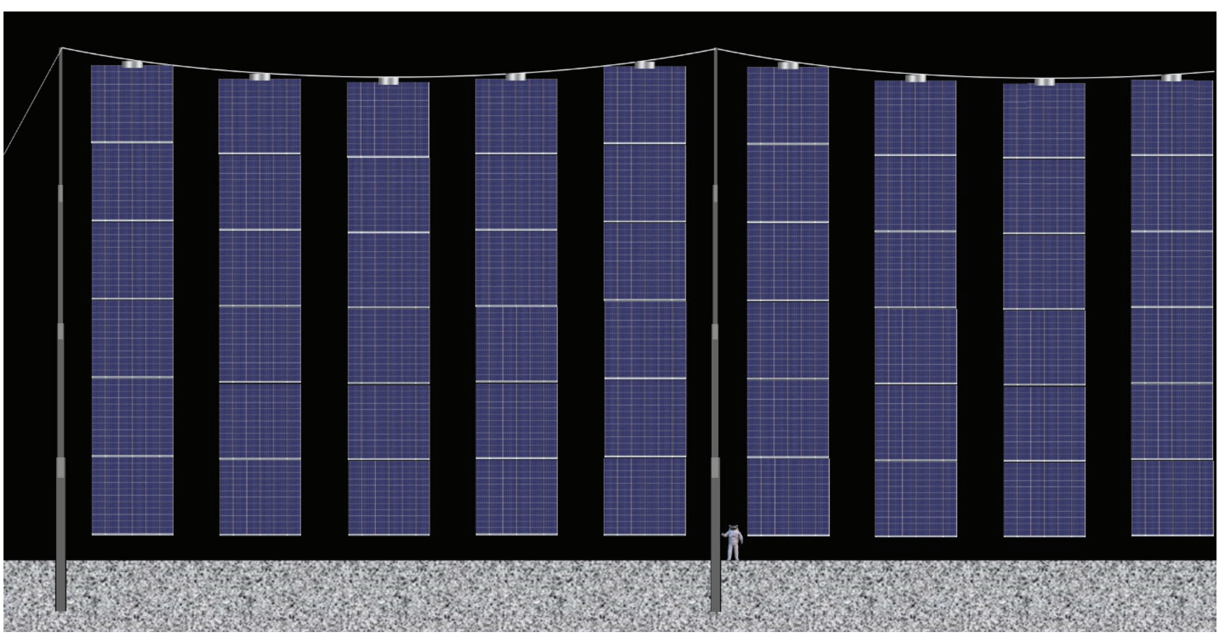
It is well recognized that the lunar south pole would be a good location for the establishment of an initial permanent base due to the presence of permanently shadowed regions near locations with nearly continuous solar illumination. If a permanent base is established and grows into a large international base, high energy activities will require the maximum exploitation of the solar power available at these high sunlight locations. These high energy processes could include: the electrolysis of lunar polar ice for propellant, the growth of food, the production of surface structures, and the extraction of metals from the lunar regolith.

The concept of solar drapes is here proposed along with a method for how they could be erected. A large payload is delivered to the lunar surface via a reusable lander. A motorized wagon with the solar drapes packed within drives out of the lander to the deployment site. An auger located at the back of the wagon drills vertical holes to a depth of approximately 20% of the height of the drapes. Automated mechanisms tilt up the first telescoping pole and places it into the hole. The holes will need to be dug as vertical as possible.

Between the tips of each telescoping pole is a suspension line onto which approximately five solar drapes are attached in series. As the wagon moves forward the solar drapes are pulled out of the wagon and onto the ground at regular intervals. The wagon then drills the second hole, tilts up and drops the second pole and moves forward thereby laying out the second section of drapes, and so on until the entire solar drape payload is set out.

The erection of the solar drapes would be as simple as activating the telescoping poles at the same time. The suspension lines between them would begin to pull up and hence deploy all solar drapes at the same time so that a long wall of solar drapes arises simultaneously. Each drape would track the sun by means of a motor between the top of each drape and the suspension line.

Calculations are presented detailing the amount of power that a single 100 metric ton payload could provide given assumptions of pole heights, supporting structures, specific power, average solar intensity, and self-shading. This is extrapolated to estimate how quickly propellant could be produced, quantity of regolith processed into metals, and number of crew able to be fed.



Research Technologies for Robotic Construction of Lunar Surface Assets. A. Quartaro[1], J. Martin[2], and E. Komendera[2], [1]NSTGRO Award Recipient, Virginia Tech Blacksburg, VA 24061, USA, [2]Virginia Tech Blacksburg, VA 24061, USA (Contact: aquartaro@vt.edu)

Introduction: To establish a long-term crewed facility on the lunar surface, aligning with NASA's goal to create a robust human lunar enterprise [1], it is imperative for the implementation of robotic technologies to assist in construction and maintenance activities. For persistent lunar presence, routine maintenance operations are inevitable. However, the cost and risk of a full EVA for crew is inefficient. Robotic assembly and maintenance technologies will greatly reduce the risk associated with EVA activities and enable the expansion of possible structures beyond pre-built modules like the ISS, allowing for piece by piece strut assembly to form. Autonomous robotics would expand the possibilities of a constructed, habitable facility before astronauts even descend to the surface.

Long Reach Manipulator Applications: The Lightweight Surface Manipulation System (LSMS) was originally developed at NASA Langley Research Center [2] to perform construction and offloading activities in a low gravity environment [3]. The tendon-actuated serial arm has a load capacity of 1000kg (Moon gravity) with a 7.5m reach [2].

A new LSMS has recently been built at the Field and Space Experimental Robotics (FASER) Laboratory, shown in Fig. 1b, with the goal to continue its use as a long-reach manipulator to assist in autonomous assembly processes. The replication of LSMS in a new labspace has allowed the design to be updated to reflect innovations in motor control and used new commercial off-the-shelf (COTS) parts that matched or improved the outdated components. In addition, the LSMS architecture was changed to implement a network based system - all motors, sensors and other potential add-ons are controlled over ethernet, with general kinematics methods remaining the same. Furthermore, a gantry system was underslung on the forearm of LSMS, improving range of motion and adding additional capabilities such as additive manufacturing [4] and dexterous manipulation.

Dexterous Manipulation: While the LSMS provides the ability for large translations for high mass loads, it does not possess the ability to perform jigging tasks. There has been extensive research into robotic dexterous manipulation [3], but such work almost always make rigid body assumptions of assets or requires crewed intervention. An operational lunar enterprise will require

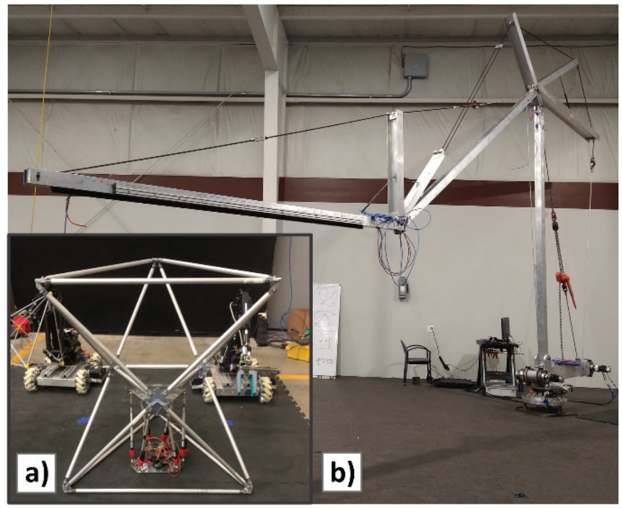


Figure 1: (a) SP for rigid/flexible operations, (b) LSMS

incoroportation of all non-structural components such as electrical routing, payload installation, solar array alignment, and maintenance tasks that require precise movements in tight quarters.

Work currently being performed under a NSTGRO Award is pursuing the use of a small scale (0.5-1 meter) dexterous manipulator, such as a Stewart-Gogh Platform (SP), shown in Fig. 1a., to be placed internal to a structure and assist in closeout assembly tasks. A model is being developed to allow for near real-time manipulation of non-rigid objects, such as cable routing and non-uniform payloads, within a confined environment. The model, Structure-Aware Simulataneous Localization and Mapping (SA-SLAM), is expected to bridge the gap between autonomous robotic technologies and the need for assembly and maintenance operations in tight quarters, where the rigid body assumption is not reliable enough to ensure success.

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Enabling Autonomous Robotics for Lunar Surface Missions and Resource Prospecting. K. Raimalwala[1], M. Battler[1], M. Faragalli[1], Rohaan Ahmed[1], M. Cross[1], E. Reid[1], [1]Mission Control Space Services Inc., 162 Elm St. West, Ottawa, ON Canada, kaizad@missioncontrolspaceservices.com

Introduction: The rise of commercial missions and activities on the Moon necessitates the shift to increasingly self-reliant system architectures to support a growing lunar economy, using on-site computing to enable real-time autonomous robotics with AI applications just as we will increasingly rely upon in-situ resources. This is critical to mitigate Earth-Moon delays, expected or unforeseen network dropouts, and data transfer constraints. Therefore, vehicles and other systems must operate to a high degree of supervised autonomy. Mission Control is developing a suite of flight software applications to allow lunar rovers to autonomously and intelligently understand the lunar surface environment and make key decisions in support of ISRU-relevant activities such as resource prospecting, excavation, and construction.

Identification of Lunar Surface Features: Any intelligent decision-making process onboard will require a semantic representation of the terrain. Mission Control has developed technology to classify known geological features at a macro-level as seen in standard colour images or identify features considered rare or novel on the lunar surface, using deep learning models (convolutional neural networks). Figure 1 shows an example output from our classifier that can detect craters, boulders, and other surface features.

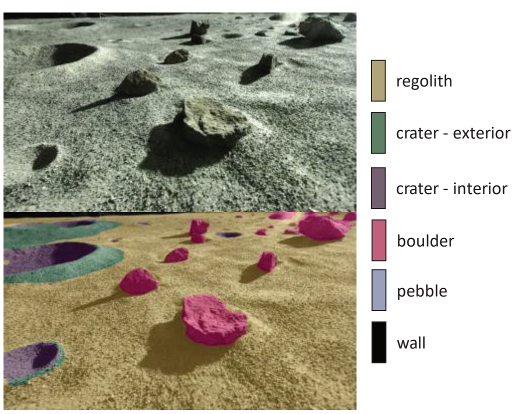

Figure 1. *Example output of our latest terrain classifier, processing an image taken from our lunar analogue testbed.*

Data Aggregation and Mapping: For geological features classified from stereo imagery (or if other correlated depth information is available), they can be projected onto a map frame and aggregated from multiple images to build a rich map-based data product that can be used by the flight software suite to enable tasks such as autonomous instrument targeting and data collection. On the ground segment, this data product can also be more easily integrated into GIS tools for rapid analysis with the context of scale and other information layers derived from *in situ* or orbital sensors. This is key to support comprehensive scientific mapping and resource prospective efforts.

Autonomous Decision-Making: Once an onboard system can infer some knowledge of the surrounding terrain's geological features, it can also be programmed with some decision-making capabilities. For rover navigation, this includes planning and executing safe and efficient trajectories that also maximize key objectives in prospecting and mining scenarios. Based on an understanding of lunar surface features, the rover can also make intelligent decisions to target payloads to collect high-priority data, and rank and prioritize data for immediate downlink to support operator decision cycles [1]. Targeted actuation such as scooping, drilling, and robotic arm operations can also be achieved autonomously using the same methodology. Mission Control can integrate this comprehensive flight software suite on a high-performance and compact processor to enable lunar rovers to autonomously conduct critical activities for resource prospecting, mining, and more. In this presentation, Mission Control will also provide an overview of participation in the ESA-ESRIC Space Resources Challenge.

Flight Demonstration: Mission Control will fly a payload on the first ispace mission M1 in 2022 and conduct the first demonstration of Deep Learning on the lunar surface, a historic milestone for space exploration. It will classify lunar geological features visible in images from the Rashid rover in the Emirates Lunar Mission (ELM). Mission Control will also participate in the international science collaboration of ELM, led by the Mohammed Bin Rashid Space Centre (MBRSC) [2].

Acknowledgments: We acknowledge the support of the Canadian Space Agency for technology development and for the lunar capability demonstration [3CAPDEMO21].

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Lunar Power Systems: Operational Challenges and Environmental Hazards. M. Rose[1], A. Sajadi[2], M. Carbone[3], and B. M. Hodge[4]. [1]CU Boulder, Megan.E.Rose@colorado.edu, [2]CU Boulder, Amir.Sajadi@colorado.edu, [3]NASA, Marc.A.Carbone@nasa.gov, [4]CU Boulder, BriMathias.Hodge@colorado.edu. (Contact: Megan.E.Rose@colorado.edu)

Introduction: The space industry is expected to establish a lasting human presence on the Moon in the coming decade [1]. A reliable and resilient electric power grid is a pivotal requirement to sustain human life on the surface of the Moon and other extraterrestrial bodies [2]. The Lunar environment introduces many novel conditions not experienced by Earth-based power systems, which will require a new approach to power system design and operation [3]-[5]. This paper describes the environmental hazards pertinent to power systems on the surface of the Moon and outlines the key planning and operating constraints of these systems. Technological and algorithmic requirements for intelligent management of Lunar power systems are discussed. Finally, potential failure modes of conventional microgrid controls in the Lunar environment are demonstrated with a DC microgrid simulation in SIMULINK.

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Scalable Roll Coating for Anti-Dust Layer based on Microscale Interfacial Instability Behavior in Polymer Nanocomposite Materials S. Liu[1], M. Harbinson[1], M. Pudlo[1], S. Khan[2], J. Genzer[2,] and J.E. Ryu[1], [1]Department of Mechanical and Aerospace Engineering, North Carolina State University, 1840 Entrepreneur Dr., Raleigh, NC 27606, [2]Department of Chemical and Biomolecular Engineering, 911 Partners Way, Raleigh, NC 27606 (Contact: jryu@ncsu.edu)

The goal of this study is to investigate a scalable manufacturing method for passive lunar dust mitigation by utilizing the roll-coating induced surface roughness on polymer composites. The 3-dimensional (3D) micro-topographical surface inspired by the Lotus leaf is generated in a fast and scalable manner to improve the dust removal efficiency by reducing the Van der Waals adhesion force [1]. In addition to the dust mitigation, the composite coating enhances the infrared (IR) emission, and therefore, is expected to facilitate the thermal radiation to lower the surface temperature in space instrumentation, such as solar panels and thermal radiators.

In this study, we exploited the instability at the interface of viscoelastic coating material and air, which spontaneously occurs due to shear stress applied by the coating roller [2,3]. Similar interfacial behavior is often observed in the texture of walls painted by the roll-brush. The custom-built two-roll coating machine was used as an experimental tool. The diameter and the length of the stainless-steel rolls are 5 cm and 30 cm, respectively. The rotation direction and speed of the rollers can be independently controlled between 0 and 360 rpm. The roller gap can be adjusted from 0 to 10 mm with 10 µm accuracy. Since the instability behavior is independent of the length of the roll, we can scale up the area of the coating layer by extending the roll length and adopting a roll-to-roll process.

We employed both SiO_2 – polydimethylsiloxane (PDMS) and TiO_2 – PDMS composites for the proof-of-concept. The purpose of SiO_2 and TiO_2 particles is to tune the viscoelasticity for the instability and absorb/emit mid-infrared (MIR) for radiative cooling [4–6]. Therefore, the composites were designed to satisfy two criteria in this study: (1) Rheology criteria: High shear yield stress and shear thinning behavior, (2) Optical criteria: Visible light transmission, and high MIR emission. The rheological behavior of the composites was measured by a temperature-controlled rotational rheometer. The shear moduli (G' and G'') and the characteristic relaxation time were characterized by the oscillatory dynamic shear test with the rheometer. The surface tension σ and the water contact angle (WCA) were measured by a goniometer. The dielectric permittivity of composites was measured by the LCR meter. The transmission and absorption of the composite films were measured by UV-visible-near-IR (UV-vis-NIR) and Fourier-transform infrared (FTIR) spectrometer. The surface roughness and topography were characterized by the scanning electron microscope (SEM) and the non-contacting laser scanning confocal microscope.

Lunar simulant (LMS-1) was purchased from Exolith Lab (FL, USA). The dust size range is 0.04 – 300 µm (mean 50 µm). The simulant was sieved into different size fractions (< 65 µm, 65 – 125 µm, 125 – 250 µm). Lunar simulant was kept in a vacuum oven at 120 – 140 ^oC for several days to dry before the experiment [7,8]. Tribocharge, which mimics the surface charge of lunar dust, will be induced on dust by tumbling the simulant against small Teflon beads in a stainless steel container [9]. The dust settlement and removal test was performed by the following procedure: 1) sprinkle lunar simulant and measure the dust weight on the anti-dust film, 2) tilt the surface 90^o, 3) measure the weight of dust that remained on the surface, 4) spin the film with 3G-force, 5) measure the weight of dust that remained on the surface.

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Deployment and Burial of Lunar Seismic Sensors using Pneumatically Assisted DIABLO. Vishnu Sanigepalli[1], Robert Van Ness[1], Kris Zacny[1], and Hop Bailey[2], [1]Honeybee Robotics, [2]University of Arizona. (Contact: kazacny@honeybeerobotics.com)

Introduction: The DALI-funded Seismic instrument is a science instrument designed to bury a sonde, seismic sensor payload, into the surface of the Moon. The burial of the seismic sensors improves the attenuation and decreases the large thermal fluctuations on the payload through a lunar day/night. The pneumatic burial system deploys the sonde with a threshold burial depth requirement of 0.6 meter and can drill up to 1.1 meters (with 0.9 clearance from tip-to-surface) into the lunar regolith, Figure 1.

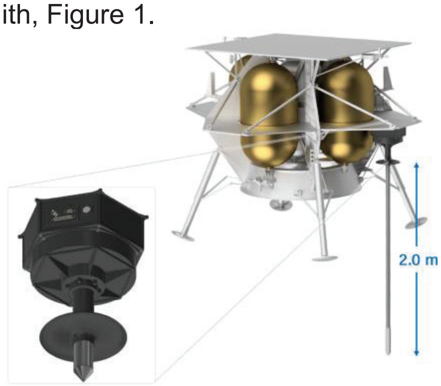

Figure 1: Instrument mounted on the belly-pan of a lander using DIABLO to deploy the sonde up to 2 meters from a stowed configuration.

The instrument's deployment technology is based on DIABLO, Deployment of Interlocking Actuated Bands for Linear Operations, which deploys a sheet metal band in a tubular form. The SS301 .005" band is stowed in a Storage Reel in a clock-spring patter and is deployed with a BLDC actuator. DIABLO's HDM, Helical Drive Mechanism, semi-permanently assembles the band together from a flat sheet to a tubular structuring with deployment and retraction capabilities. The retraction capability of the system is used to recover from obstacles by the dither operation, which dislodges rocks obstacles and convey them to the surface.

The gas for pneumatic drilling is fed through a PTFE tube that is deployed in spiral-like fashion and expands like a telephone cord within the ID of the tube along the sensor/power lines for the seismic sensors shown in Figure 2. The gas is emitted to the nozzles of the sonde housing that expands in the vacuum and excavates the regolith. The flow of gas that is stored in tanks is controlled via a series of pressure transducers, valves, and sensors that are autonomously controlled by avionics during deployment.

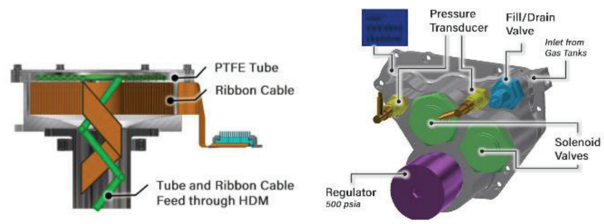

Figure 2: Pneumatic gas controlled via the manifold is conveyed through a PTFE Tube. A Ribbon Cable power and provides DAQ of seismic sensors.

After the sonde reaches the desired depth, the pneumatic system PWMs the gas to self-bury the sonde by depositing regolith onto itself to increase sonde-to-regolith coupling. A release mechanism is used to mechanically detach the sonde and retract the DIABLO structure to prevent any vibrations or thermal shocks that be transferred from the lander. An umbilical ribbon cable spooled out to ensure the sonde does not get dislodged from the surrounding regolith (Figure 3).

Testing and Demonstration The instrument has been demonstrated in a vacuum chamber at 7 Torr with a vacuum compacted BP-1 Fines [1]. The system has penetrated up to 0.8 meters autonomously. These tests have demonstrated and increased the end-to-end instrument mechanism and ConOps to a TRL 5/ 6 along with capturing the data from the seismic sensors to detect earthquakes.

Figure 3: (left) Instrument in stowed configuration (middle) Deployed stated after burial of sonde (right) Sonde deployed at target depth with umbilical ribbon cable.

References:

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Acknowledgements: This work is funded under NASA DALI program.

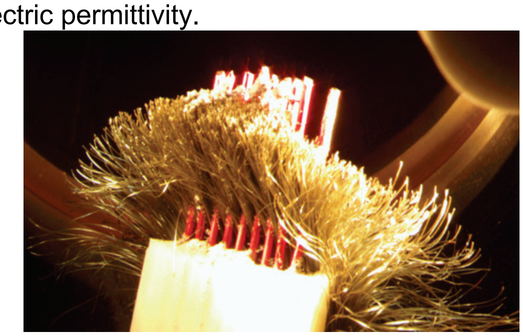
Novel developments in Electrodynamic Dust Shield (EDS) technologies for lunar dust mitigation. M. J. Schaible[1], K. G. Sjolund[1], M. E. Judson[1], E. A. Ryan[1], M. L. Shofner[1], J. S. Linsey[1], and T. M. Orlando[1], [1]Georgia Institute of Technology, 901 Atlantic Dr., Atlanta GA 30332. (Contact: thomas.orlando@chemistry.gatech.edu)

Introduction: The return of manned missions to the moon requires novel solutions to the unique problems posed by lunar dust. One technology that has been identified as a promising dust mitigation solution is Electrodynamic Dust Shielding, or EDS [1]. EDS is an active dust mitigation technique which uses alternating electric fields applied to pairs or sets of interdigitated electrodes to remove lunar dust from surfaces. While EDS has been shown to be effective for several applications and form factors [2], further development and combination with other mitigation solutions is needed for EDS to be safe and reliable for lunar surface operations. This presentation will describe recent work at Georgia Tech investigating novel EDS solutions including (1) new materials and form factors for planar (2D) EDS, (2) the effects of surface coatings, UV, and electron bombardment on the effectiveness of EDS, and (3) the design of a 3D-EDS system for brush cleaning.

Chemically modified reduced graphene oxide (CMrGO) EDS systems: Although EDS has long been studied as a promising dust mitigation solution, previous systems often require high voltages and rigid form factors for operation. The goal of the SSERVI REVEALS team is to design systems that operate at lower applied potentials, that can be quickly and easily manufactured, and that can be easily combined with additional dust mitigation solutions (e.g., electron bombardment or passive coatings). Leveraging recent work from the SSERVI REVEALS program on the development of chemically modified reduced graphene oxide (CMrGO) [3,4] planar EDS systems have been created through a surface lamination technique which produces a surface-localized, electrically conductive nanocomposite which serves as the electrode material. This material is beneficial as it can be blended into bulk polymers or laminated onto a wide range of thermoplastics in a range of patterns [4]. Initial testing with rGO based EDS will be discussed.

Combinations of mitigation solutions: The smallest grains in the lunar regolith (<5 um) are both the most toxic and the most difficult to remove from surfaces. EDS is typically most effective for large grains, and thus testing is ongoing to combine the CMrGO-based EDS systems with other mitigation solutions that have been shown to be effective for small grains. Additionally, previous tests on copper EDS patterns showed that exposing the dust grains to a high-intensity UV source significantly lowered the voltage at which the EDS began to mobilize the dust grains. Tests are ongoing to determine the effects of exposing CMrGO devices to the UV source and low energy electrons from a filament emission source [5].

Development of 3D-EDS: The 3D-EDS development is aimed to create an EDS enabled brush that astronauts can use to clean their spacesuits while on EVA. Initial experiments for this involved using enamel coated copper wires held amidst the bristles of a brush. While movement was recorded when this setup was tested with bristles made of Nylon and Thunderon®, the repulsion was not as significant as desired. Further experiments are planned to incorporate more electrodes into the bristles and to use bristle materials with higher dielectric permittivity.



Thunderon brush with 3D-EDS. Severe bristle deformation due to resistive heating of electrodes and radiative heating from UV lamp.

This work was directly supported by the NASA Solar System Exploration Research Virtual Institute (SSERVI) under Cooperative Agreement #NNA17BF68A (REVEALS). It was also a part of the 2021 NASA's BIG Idea Challenge as a part of team Shoot for the Moon from Georgia Institute of Technology.

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Overview and Progress of the Motors for Dusty and Extremely Cold Environments (MDECE) Project.
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Introduction: Conventional, grease-lubricated actuators for space mechanisms can achieve long life but must be heated above about 213 K, or -60 °C, to function in cold environments. In extremely cold environments like lunar permanently shadowed regions, the penalty for heating can be a 5% to more than 80% reduction in the actuator's perceived efficiency, depending on its concept of operations and emissivity of its housing [1]. An established alternative is to use actuators lubricated with solid lubricants, which don't require heating but have limited life and are subject to much stricter design constraints on bearing/gear loading and speed. NASA's Motors for Dusty & Extremely Cold Environments (MDECE) Project is a research and technology (non-flight) project developing two rotational actuators that can achieve long life without the need for supplemental heating. This poster/presentation will provide an overview of the project's objectives, key driving requirements, approach, test plan, and results to date.

MDECE Project: The MDECE actuators will be developed from a technology readiness level of 2 to 5. They will exhibit the aforementioned benefit by eliminating the biggest tribological challenge – lubrication of mechanical gears – and utilizing solid lubricated bearings. One actuator realizes this by employing non-contact magnetic gears. The other actuator naturally produces the desired slow output rotation speed and thus does not need gearing.

Each actuator is being developed for the lunar surface to have a minimum operating temperature of -165 °C (108 K) to -243 °C (30 K). The other key performance parameters include the life of each actuator in a dust free environment, the efficiency of the magnetic actuator, and the output resolution of the piezoelectric actuator.

The scope of the project includes: the development, manufacture, and relevant environment testing of each actuator; the effect of lunar regolith simulant on each actuator's life; the compatibility of each actuator with its drive/controller; and testing of commercial off-the-shelf actuator components. The scope does not include the advancement of bearing technology, dust seals, or stand-alone dust mitigation technology.

Magnetic Actuator: The magnetic actuator is being developed for a requirement set that is relevant for rover mobility and robotic arm joint actuation. It is composed of a magnetically-geared motor connected to a magnetic gear. The key driving requirements and a brief overview of the preliminary design will be presented.

Piezoelectric Actuator: The requirements levied on the piezoelectric actuator development are relevant for precision positioning applications. The key driving requirements and a brief overview of the preliminary design will be presented.

Test Plan: Relevant environment testing of each actuator will be conducted in a dirty thermal vacuum chamber at the Kennedy Space Center. The test campaign will include: dust-free testing to demonstrate the actuation performance and identify the upper and lower operating temperature limits; a dust-free life test; a life test in a dusty environment; and a hot survival test.

Current Status: A preliminary design review of each actuator was recently passed. Limited risk reduction testing has been completed with more finishing in the April to July timeframe. The dirty thermal vacuum chamber has been commissioned and will soon be used to test commercial off-the-shelf actuator components.

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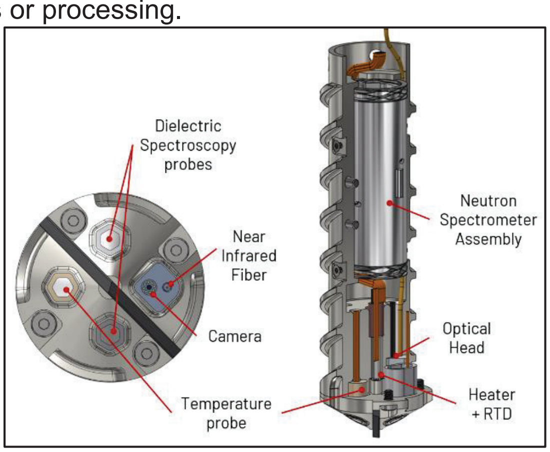
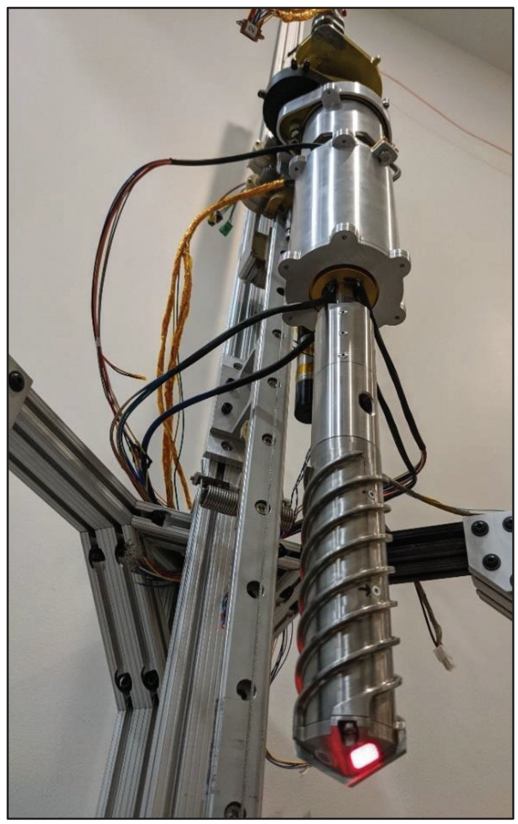
SMART: Instrumented Drill for ISRU Investigations on the Moon. Leo Stolov[1], Kris Zacny[1], Jennifer Heldmann[2], Kathryn Bywaters[1], Carter Fortuin[1], Sofia Kwok[1], Anthony Colaprete[2], Arwen Dave[2], Richard Elphic[2], Dayne Kemp[2], Keith B. Chin[3], [1]Honeybee Robotics, 2408 Lincoln Ave, Altadena, CA 91001, [2]NASA Ames Research Center, Moffett Field, CA 94035, [3]Jet Propulsion Laboratory, 4800 Oak Grove Drive, Pasadena, CA 91109 (Contact: lastolov@honeybeerobotics.com)

Introduction: SMART (Sensing, Measurement, Analysis, and Reconnaissance Tool) is a next generation drilling system for lunar ISRU applications. SMART is a rotary percussive drill mounted on a linear stage, similar to The Regolith and Ice Drill for Exploration of New Terrains (TRIDENT) that is flying to the Moon in 2022 and 2023 [1]. Unlike TRIDENT, which uses the auger to move drill cuttings up to the surface for analysis, the SMART auger and bit assembly is integrated with instruments that can perform analysis in situ. By instrumenting the auger, we are changing the paradigm of exploration – we are bringing an instrument to the sample as opposed to bringing the sample to an instrument.

Instruments: SMART is instrumented with five sensors in a 2 inch (5.08 cm) diameter auger and bit assembly: (1) neutron spectrometer for hydrogen detection, (2) near infrared spectrometer for volatiles and mineralogical information, (3) dielectric spectroscopy probe for electrical properties, (4) temperature sensor and heater for thermal gradient and thermal conductivity measurements, and (5) camera for visible light images and surface texture. The drill is also an instrument, as drilling power and penetration can be used to determine regolith strength. The chosen sensors are used to “sniff” for water ice and determine volatile composition thus allowing for high-grading lunar sample. SMART allows missions to make to make educated and expeditious decisions as to whether the downhole soil sample should be delivered to any rover mounted ISRU instruments for further analysis or processing.



System design: SMART consists of several major subsystems: a rotary-percussive drill head for providing percussion and rotation to the drill string, a linear stage for advancing the drill string into the subsurface, an instrumented drill string, a slip ring section to feed the electrical signals to a data acquisition box, and a fiber optic rotary joint section to feed the optical signal out to the near-infrared spectrometer. A prototype has been developed with the goal of demonstrating instrument functionality and testing in a relevant lunar environment. SMART can be mounted to a lander, rover, or even be adapted as a handheld system for high grading on the lunar surface as part of the Artemis program.



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Determination of Material Durability for Sustained Lunar Applications Using Solid Particle Erosion

D. Malik Thompson[1] and Getu Hailu[2]

[1] Aerospace Materials Engineer, EM41, Nonmetallic Materials and Advanced Manufacturing Division

[2]Department of Mechanical Engineering, University of Alaska Anchorage

NASA has identified that “the key to sustained lunar surface presence will be an optimization of materials, designs, and innovative techniques used to mitigate the effects of lunar regolith dust.” As such, NASA has made it a priority to assess the durability of state-of-the-art materials (i.e. seals, coatings, and structural materials) against simulated lunar environments in order to select combinations of these materials and surface preparations to better enable lunar surface missions. In this work, cryogenic solid particle erosion (cryogenic SPE) wear resistant properties of materials developed for lunar surface missions were assessed and materials were ranked according to their cryogenic SPE wear resistant capabilities. This was achieved by establishing an experimental setup for cryogenic SPE and conducting cryogenic SPE experiments at six angles of impact. Observations made using SEM and microscopy reviled the material removal mechanism.

Waste Heat-Based Thermal Corer for Lunar Ice Extraction. Kuan-Lin Lee[1], Quang Truong[1], Sai Kiran Hota[1], Calin Tarau[1] and Kris Zacny[2], [1]Advanced Cooling Technologies, Inc., Lancaster, PA, 17601, [2]Honeybee Robotics, Altadena, CA, 91001. (Contact: kuan-lin.lee@1-act.com, quang.truong@1-act.com)

Introduction: The water/ice accumulated in the Permanently Shadow Regions (PSR) of the Moon is considered to be the most valuable resource, since it can be processed to generate Oxygen for life-supporting and converted into LH2 and LO2 for satellite and spacecraft refueling. Such water can be extracted from icy-soil through in-situ heating and then collected by re-freezing the sublimated vapor within a cold trap container. Under this research, a thermal management system (TMS) for Lunar Ice Miners was developed, which consists of a waste heat-based thermal corer that can strategically use the waste heat of on-board nuclear power sources for ice extraction, and a cold trap tank than can use the lunar cold environment as the heat sink for ice collection. The thermal corer includes embebded mini-channels into the drill's wall. The hot incoming fluid splits into 4 mini-channel passages near the top of the corer and flows downwards closer to the inner side of the thermal corer. This mechanism allows for more residence time of the hot fluid, thus, more heat is dissipated for sublimation. In order to investigate heat exchange between the corer and icy-regolith during the thermal extraction process, a two-dimensional transient model was developed and built-in ANSYS FLUENT environment as user defined functions (UDF). The UDF provides the user-defined material properties of the icy-regolith as a function of temperature and porosity, including specific heat, thermal conductivity, saturation pressure, and mass fraction of ice. Verification of the phase-change mechanism of the thermal model was performed by extracting the temperature profiles of three locations inside the corer at the same time frame, and parametric sensitivity study was performed with different flow rates, pumping powers, and back pressures. In addition, the model was validated against experimental water extraction of Mars regolith and Lunar regolith. Both experiment and simulation demonstrated a complete sublimation 10% wt of icy-soil within ~ 9 minutes, using a thermal corer with 6 inches in length, 0.6 inches in inside diameter, and wall temperature of 57 ℃. The research work in this paper was performed as a part of on-going NASA Small Business Innovation Research Phase II (Contract: 80NSSC21C0564) program, awarded to Advanced Cooling Technologies, Inc.

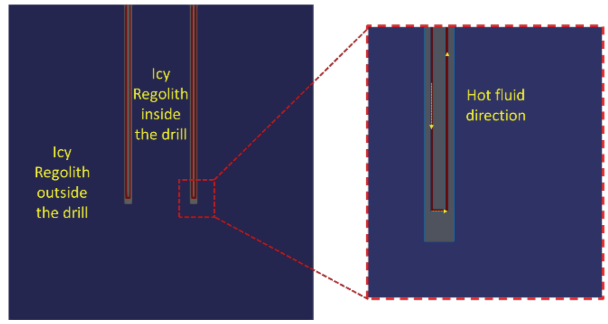


Figure 1. FLUENT Domain of the thermal corer in icy-regolith environment. The corer is in gray. The icy-regolith is in blue color. The heat transfer fluid is in red color. The arrows show the the fluid direction, from top left to top right, to provide heat to the corer.

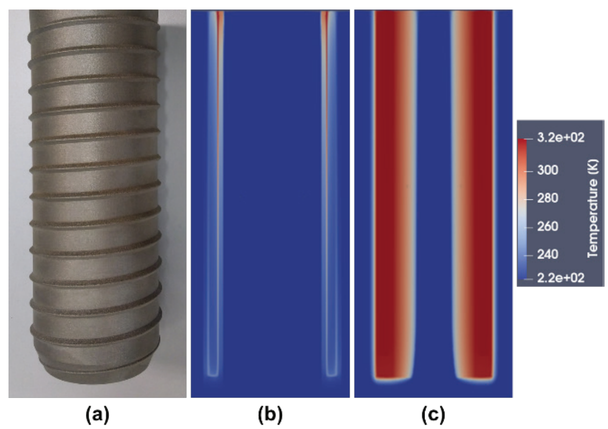
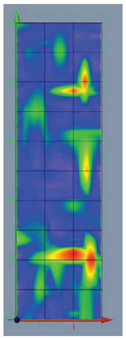


Figure 2. (a) Thermal corer 3D-printed in stainless steel, (b) Temperature profile of FLUENT simulation at time = 1s, (c) Temperature profile of FLUENT simulation at time = 300s.

Thermal Cone Penetrometer and Ground Penetrating Radar Testing Progress for Determination of Lunar Regolith Geotechnical Properties and Volatile Characterization. P.J. van Susante[1] J. Allen[1], T.C. Eisele[1], T. Scarlett[1], and K.A. Zacny[2], [1]Michigan Technological University, 1400 Townsend Dr. Houghton, MI 49931, [2]Honeybee Robotics, 2408 Lincoln Avenue, Altadena, CA 91001. (Contact: pjvansus@mtu.edu)

Introduction: As part of the inaugural NASA Lunar Surface Technology Research (LuSTR) program [1] Michigan Technological University in collaboration with Honeybee Robotics was selected to develop a dynamic hot cone penetrometer (DHCP) in combination with ground penetrating radar (GPR) to characterize lunar geotechnical properties and the presence and quantity of volatiles. After 10 months of work, good progress has been made.

Test Hardware: The work has been divided into several tasks. The three main tasks worked on so far have been to 1) test several cone penetrometers, 2) test thermal heating of regolith and water/ice and, 3) test GPR in the field to detect ice and rocks. Several test setups and prototype hardware have been developed including a 1.05mx1.05mx1.22m regolith sandbox in which several custom instrumented cone penetrometer tests can be performed and compared with ASTM standard cone penetrometer testing, without affecting eachother while only having to prepare the compaction levels and ice content layering once to minimize variation in comparison tests due to preparation variability. For the heated cone we developed a testbed to measure the heat affected zone in regolith with a varying percentage of water or ice (zero-10 wt%). The data collected with 24-40 thermocouples at various locations/distances from the heater allowed us to measure the thermal profile and variation with different power levels for the heater. Phase changes and heat affected zone can be clearly seen in the data. A new testbed is being developed to measure similar response curves for cryogenically frozen volatiles. For the GPR we have created a field rover (HOPLITE) that can carry the GPR and the Percussive Hot Cone Penetrometer (PHCP) in the field test. This past summer and this winter we have tested the field rover as well as successfully buried ice and other targets in the basalt sands to be detected by the GPR.



Design Progress: An initial prototype for the PHCP is being designed. The percussive head and z-stage have been designed and are being finalized while the cone penetrometer concepts are being developed based on the geotechnical and thermal experiments and modeling performed to date.

Testing plan and deliverables: Testing will continue under lab and field conditions using cryogenically frozen regolith simulant and volatiles in the lab and two field sites. This coming summer, further field rover testing will be performed and next winter, a trench filled with different icy layers of regolith simulant to test the DHCP and GPR in a natural frozen basalt sand environment where we will create known underground ice and rock objects and ice layers to identify with GPR. Separate frozen icy regolith simulant test layers will be created in a large 40ft freezer container for testing the geotechnical property determination using the DHCP as function of ice content and percussive frequency and energy.

Conclusion & Future work: The project is progressing well despite some COVID challenges. We hope to fly the PHCP and GPR on a future CLPS mission.

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Thermal mining of icy regoliths: production decline mitigation.

T. G. Wasilewski, Astronika Sp. z o. o., gwasilewski@astronika.pl

Introduction: Extraction of ice in Permanently Shadowed Regions of the Moon using the thermal mining method may follow distinct production phases closely related to the build-up of a sublimation lag and loss of bulk thermal conductivity [1]. Negative feedbacks in lunar water production, capture and processing need to be closely studied and mitigated using operational and technological methods. Two novel production methods are especially promising: (1) continuous thermal mining, utilizing fast removal of the sublimation lag, and (2) fracking thermal mining, utilizing injection of a high thermal conductivity material into icy regolith porous space and fractures. These two methods are studied in homogenous and heterogenous icy deposit conditions using combined heat and mass transfer model, and are compared with the baseline thermal mining method yields. Technical feasibility of those methods is also discussed. Production improvements are observed across different production scenarios. This proves that maintenance of bulk high-thermal conductivity in the mined deposit may improve water production in PSRs, while new systems and operational strategies have to be included in the development of ice extraction infrastrcucture. Thermal mining once again proves that it is a very promising architecture for development of the cislunar econosphere, showing yields of thousands of metric tonnes of water per extraction.

Modelling: Based on the previous time-dependent combined heat and mass transfer model found in [1] and [2] (baseline scenario A), an extended variability was introduced to investigate different extraction scenarios, with addition of bulk regolith depth-dependence (scenario B), ice content depth dependence (scenario C), lowered ice density (scenario D), and continuous sublimation lag removal (scenario E). As in the baseline investigations, focus is set on the phase change interface and its behaviour, as it can be easily translated to water production and production rates. The continuous lag removal is modelled with mesh movement governed by the limit on icy fraction in nodes. The lag removal is consistent with continuous scraping or blow-off of the hot sublimation lag, as the extraction progressed deeper.

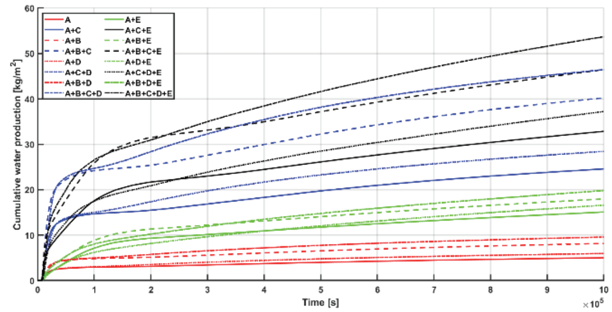

Figure 1. Cumulative production across different scenarios.

Discussion: Across the different scenarios, yields are increased relatively to the baseline. Such observations can be made:

- Bulk thermal conductivity is the main production factor during thermal extraction of ices – the extraction systems should aim to keep this parameter high, whenever possible. Introduction of non-icy high-TC materials in the deposit (through fracking) may be advantagous;
- Heterogenous, depth-increasing distribution of ice and regolith density positively affects production yields;
- Exposure of ‘fresh’ ice, especially in heterogenous deposit, is advantageous;
- Regardless of the scenarios, production still follows distinct production phases, with high production rates at the beginning, and slow decline in time.

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[2] T. G. Wasilewski, T. Barciński and M. Marchewka, "Experimental investigations of thermal properties of icy lunar regolith and their influence on phase change interface movement," *Planetary and Space Science,* vol. 200, 2021.

Passive nonlinear thermal devices leveraging temperature-dependent magnetic forces.

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Introduction: Novel passive thermal management technologies could enable improved temperature (*T*) regulation for lunar surface applications that experience large environmental *T* variations due to the diurnal cycle. Existing conduction heat switch technologies have used thermal expansion of waxes [1], metals [2], or shape-memory alloys[3] to make/break thermal contact between mirror-polish surfaces as a function of *T*, leading to a highly nonlinear thermal response. These heat switches are relatively mature technologies with impressive thermal conductance turndown ratios, but often require relatively large (>5 cm) thicknesses and ultra-narrow (<1mm) gap sizes.

Mechanism: Our passive nonlinear thermal devices make and break thermal contact between surfaces by leveraging the *T*-depedent magnetization of the ferromagnetic material gadolinium (Gd) near the Curie temperature of T_c~20ºC. When the Gd *T* is below T_c, there is a attractive magnetic force between Gd and a permanent neodymium (Nd) magnet that can be used to open/close a gap between thermally conducting surfaces. When the Gd *T* is above T_c, this Nd-Gd force vanishes and additional *T*-independent forces actuate motion to make/break thermal contact. The magnetic actuation mechanism is reversible (typical thermal deadbands ~5ºC), amenable to ~1 cm device thicknesses, and does not require sub-mm gap sizes.

Devices: Fig. 1 shows our three passive thermal management devices that leverage *T*-dependent Nd-Gd interaction. Fig. 1(a) illustrates an oscillating thermal diode inspired by previous research using microfabricated Gd devices [4]. The oscillations of our macroscopic diode enable unidirectional heat transfer when the *T* bias is aligned with the direction of gravity, and have achieved thermal rectification ratios >25 in ambient enviroments. Fig. 1(b) illustrates a non-oscillating thermal relay, which is a three-terminal device in which the Gd *T* gates the heat flow from the thermal source to thermal drain. Lastly, Fig. 1(c) shows a non-oscillating passive magnetic heat switch with 11 mm thickness and switching *T* near 15ºC. These devices could enable new opportunities for passive thermal management of lunar rovers and habitation under time-varying thermal loads.

Acknowledgements: This work was supported by an Early Career Faculty grant from NASA's Space Technology Research Grants Program (Grant #80NSSC20K0066) and a NASA Space Technology Graduate Research Opportunities Award (80NSSC20K1220).

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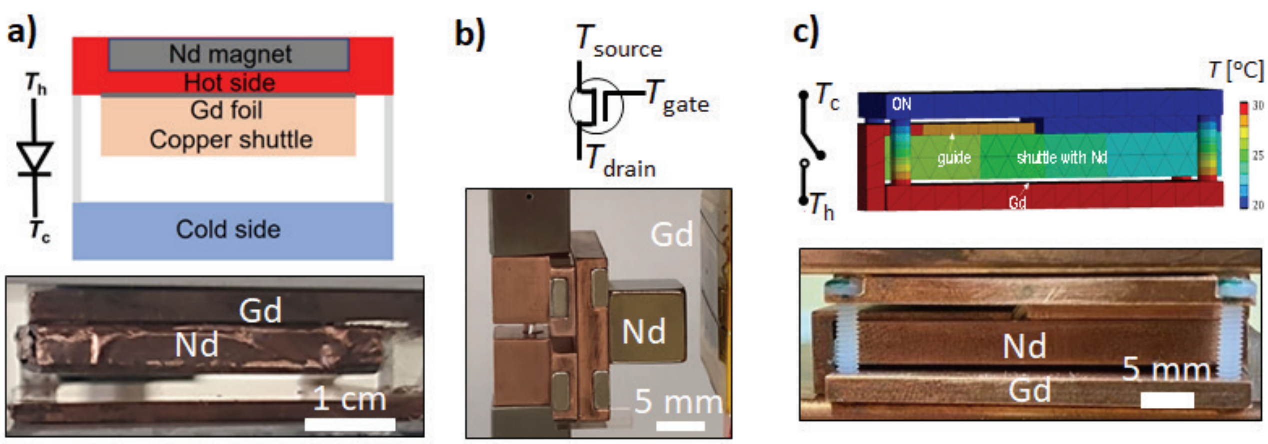

Figure 1. Design and implementation of Gd-based (a) oscillating thermal diode, (b) thermal relay, and (c) passive thermal switch for improved thermal management.

To reduce energy requirements for lunar bricks, sort the regolith to increase amorphous content.

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Introduction: Exploration of the lunar surface and long-term habitation require construction using *in situ* resources. In order to determine the range of energy consumption required for production of construction materials from lunar regolith, we conducted heating experiments on a series of lunar simulants.

Methods: The two compositional end-members are anorthosite, from Stillwater MT, and basaltic JSC-1A simulant. We studied both rock powder and remelted glasses for each one. We then used differential scanning calorimetry to measure the energy required to melt ten combinations of anorthosite and basalt, with different degrees of crystallinity. We heated ~30 mg of material to 1500˚C at 30˚C/minute.

Results: Enthalpies required to go from 50˚C to complete melting are 1775 Jg^{-1} for JSC-1A and ~1890 Jg^{-1} for a 50-50 mixture by weight of JSC-1A and anorthosite. The total enthalpies required to achieve melting are systematically lower for glassier starting materials, for example 1564 Jg^{-1} for remelted JSC-1A and 1669 Jg^{-1} for a 50-50 mixture. Starting materials containing glass undergo crystallization above the glass transition (~650˚C for JSC-1A glass and ~850˚C for anorthosite glass), releasing up to 250 Jg^{-1} of latent heat.

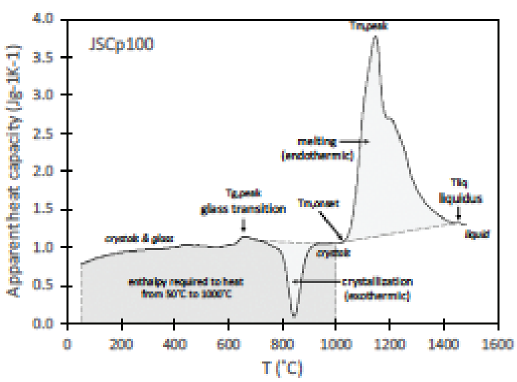

Fig. 1 Apparent heat capacity vs temperature for JSC-1A (powder). T_g = glass transition temperature. Light grey shaded fields are enthalpies of crystallization, and of melting

Sintering can produce crystalline samples without needing to heat much above ~1000˚C, and the release of latent heat of crystallization makes this a very energetically efficient approach, with enthalpies required to heat to 1000˚C as low as ~810 Jg^{-1} (Ag50Jg50). Full results are presented in [1].

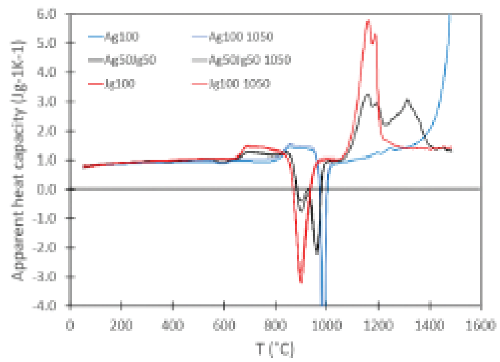

Fig. 2 Apparent heat capacity vs temperature for glasses made by remelting JSC-1A (red), anorthosite (blue), and a 50-50 mixture by weight (black), showing the effect of glass composition.

Implications: Rather than remelting regolith completely at the liquidus temperature, bricks could be produced at lower energy cost by sintering starting materials with a glassy component, sourced from volcanic or impact melt deposits.

The tendency for finer grained lunar regolith to also be more feldspathic and glassy [2,3] raises the possibility that physical sorting by size can also sort for composition and crystallinity, facilitating brick production in locations where the bulk regolith is less suitable.

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Concentrated Solar Molten Regolith Electrolysis Hunter Williams[1], Timothy Newbold II[1], Joseph Hernandez[1], Kathryn Bywaters[1], [1]Honeybee Robotics, 2408 Lincoln Ave, Altadena, CA
Contact: hjwilliams@honeybeerobotics.com

Introduction: The great majority of the Lunar surface is made of oxidized minerals. This oxygen can be separated from the base metals and metalloids by melting the regolith and putting it through an electrolysis process. Terrestrial electrolysis processes use an electrolyte to optimize temperature and chemistry, but these electrolytes are consumables and have not yet been developed for efficient reuse in a high throughput system. Honeybee Robotics has been developing a molten regolith electrolysis system for Lunar use. To rapidly test new designs for components such as electrodes, sensors, and volatile control mechanisms for this system, Honeybee Robotics has constructed a concentrated solar simulator and test bed. Honeybee is using this simulator to melt regolith simulant for integration into the GaLORE (Gaseous Lunar Oxygen Regolith Electrolys) system in partnership with SwampWorks at NASA Kennedy Space Center.

Molten Regolith using Lunar Simulant: Tests were performed to compare molten regolith in open air to molten regolith produced in vacuum. JSC-1A was used for this test in both cases using the same power intensity, focal distance to the regolith surface defocused to a 10 cm diameter, and 10 minutes exposed to the light emitted by the xenon short arc lamp. The cooled samples from both cases are shown below (Figure 1).

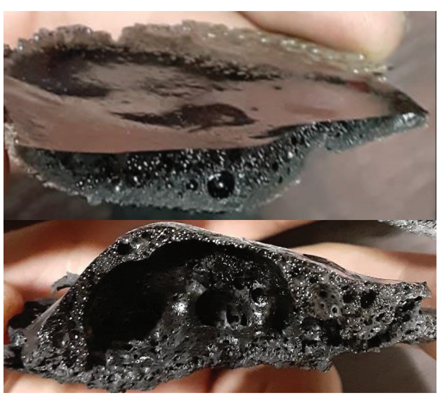

Figure 1: JSC-1A samples after being produced and cooled in open air (Upper) and in vacuum (Lower).

The results show that the major and minor diameter is consistent in between the two cases, 8 cm and 5 cm respectively. The thickness, however, varies between the two. In vacuum, there is no atmospheric pressure to keep the surface tension of the molten regolith from pushing upwards as the core of the molten pool is outgassing. This outgassing causes bubbling on the surface while the melt is occurring and give the sample under vacuum a very porous structure. A thin layer of molten material keeps the bubble together, but cools extremely rapidly once the heating source is removed and crumbles under slight pressure when refrozen. The cooling is so rapid that overall density of each sample can vary by an order of magnitude depending on whether the system is turned off during or after internal bubble formation.

Figure 2: Electrode gap variance.

Component Tests and Variations: Honeybee has experimented with variance in electrode material, shape, and gap. Preliminary results indicate that lower temperature melt pools have higher dynamic instability and do not reach a steady state electrically for sustained and predictable electrolysis. Voltage driven ameperage spikes indicate that joule heating is necessary even when a melt pool has formed. Time dependent amperage spikes indicate that paths of least resistance are forming, electrolysis is happening in those paths, and then evolved oxygen may be blocking further electrolysis. Visible differences can be seen in melt pool quality when gaps of different sizes are used: much smaller bubble formation and larger pools of electrolyzed materials form when the system is oriented for joule heating with a smaller electrode gap (Figure 2, right). Variation on these components and test parameters are ongoing, with the goal of constructing a flight-forward model for integration into a CLPS sized payload within the next two years.

Acknowledgements: This work was performed as part of the Gaseous Lunar Oxygen Regolith Electrolysis (GaLORE) NASA Early Career Innovation award.
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Lunar Array Mast and Power System (LAMPS) for Deployable Lunar Power Provision

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Introduction: The key challenges to sustained human presence and in situ resource utilization (ISRU) activities on the Moon are mass, dust, and power [1]. With sufficient power, surviving lunar night and working in the permanently shadowed regions are feasible. Solar power is an enabling resource anywhere at the Lunar surface, and a solar powered micro grid at the Lunar poles would be useful to mission planners, scientists, engineers, astronauts, and the Department of Defense. Lunar permanence starts with steadily available power.

Honeybee Robotics (HBR) and mPower are developing the Lunar Array Mast and Power System (LAMPS) to provide such power for the first time. This lightweight and relocatable robotic system combines key technologies for solar photovoltaic power generation, dust tolerant connection points, zero maintenance actuation, compact deployment, and autonomous operation (Figure *1*).

LAMPS is a deployable solar panel system that allows for operation 8 meters above the ground with solar panels extending another 10 meters. LAMPS, in its current architecture, is designed to provide 10 kW of electrical power, assuming various system level and solar array inefficiencies. This extended height, deployed at certain locations on the Lunar surface, will allow LAMPS to operate with a drastically reduced period in darkness, of around 5 Earth days or less.

Design: LAMPS' underlying robotic technologies from HBR have been designed for drilling hundreds of meters into lunar and Mars regolith [2] and thus are inherently robust and dust tolerant. LAMPS' solar cell technology from mPower, called DragonSCALES, is what makes LAMPS low mass and low volume. DragonSCALES-based solar arrays are half the mass per kW of traditional space solar arrays. This drives a smaller structure and overall system mass. The key LAMPS design elements include:

1. Stowable lightweight solar panels based on DragonSCALES
2. Solar panels deployment based on TRIDENT cable-pulley architecture
3. Redeployable mast based on DIABLO
4. Redeployable umbilical cable
5. HBR actuators for deployment, leveling and solar tracking
6. Dust tolerant electrical connectors
7. Thermal control system
8. Power storage and battery management
9. Avionics and communications based on TRIDENT
10. Autoleveling based on HBR robotic systems

Work Done to Date: LAMPS is made up of various HBR technologies funded over the years through numerous NASA programs including SBIR, DALI, and CLPS/PRISM. The subsystems are used in HBR drills, pneumatic excavators, and robotic actuators. LAMPS is funded through the Lunar Vertical Solar Array Technology program. Honeybee has also designed systems similar to LAMPS for single-deployment, permanent electrical power provision at large scale.

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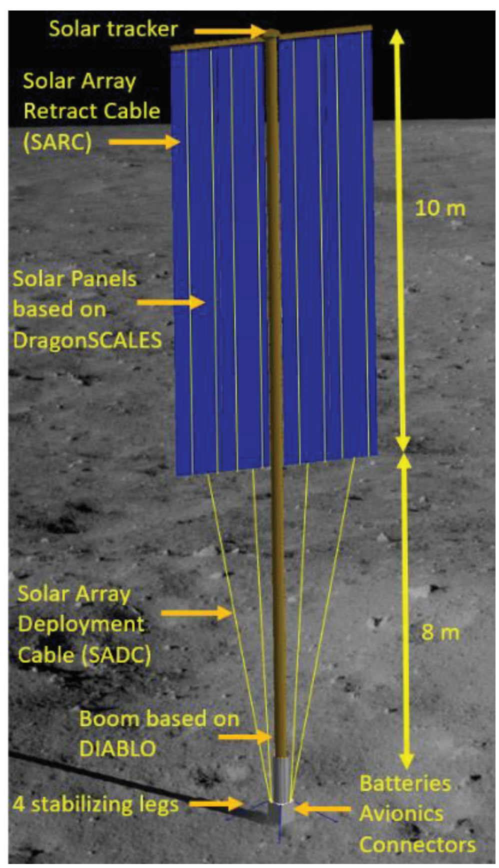

Figure 1:LAMPS and major subsystems.

Developing Mass Spectrometry for Water Quantitation and Volatiles Analysis from In-Situ Lunar Regolith

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Introduction: With a revived focus to create a sustainable human presence on the moon, and in preparation for future Mars exploration, it is imperative that all resources are utilized to their fullest potential [1]. In-Situ Resource Utilization (ISRU) will be critical for future mission success as it would enable independent operation of missions while reducing the dependence on the complex supply chain created between the Earth, the moon and Mars.

One of the most critical resources that has been identified for ISRU on the lunar surface is water [2]. Water is a versatile resource that can be used in various space operations, such as radiation shielding and conversion to oxygen (O_2) for propellant [3,4]. One of the most water rich resources is thought to be within the regolith located in the permanently shadowed regions (PSR) of the Moon; several upcoming missions, such as PRIME-1 and VIPER, are already scheduled to confirm this hypothesis [5,6]. However, there are currently no missions planned to quantify the abudance of water at these regions. The quantity of water contained in the ice will inform and help the development of future ISRU plants and operation.

Water and other volatile gases can be detected upon controlled heating of icy lunar regolith for an accurate quantification of water. This method is similar to thermogravimetric analysis, which was used to analyze Apollo lunar regolith samples. However, losses via sublimation/evaporation or contamination may have occurred with the samples due to the transit and exposure to the terrestrial environment. Furthermore, water would not be expected for these samples since they were not collected from a PSR. Thus, for more accurate results, icy lunar regolith should be analyzed *in situ* to provide the most representative composition of both water and other volatile gases.

The Light Water Analysis and Volatile Extract (LightWAVE) project aims to address this knowledge gap. A system has been developed to collect, heat and analyze evolved gases from lunar regolith on the lunar surface. The gases will be analyzed by a modified commercial off the shelf (COTS) residual gas analyzer (RGA) quadrupole mass spectrometer. Evolved gases from heated regolith samples can be identified by the observed mass-to-charge (*m/z*) ratios, and the peak intensities correlate to the abundances of the observed gases for quantitation. Therefore, our group is developing a calibration methodology utilizing a COTS RGA to quantitate water from in-situ regolith samples on the lunar surface. The partial pressure of water and ideal gas law will be used to quantify the total water evolved from a regolith sample. Here we present our methodology for the design and calibration for water quantitation using a COTS RGA.

Acknowledgments: We want to thank Aaron Paz, Naina Noorani, Anastasia Ford, and others from NASA JSC for their collaboration on this work. This project is funded by the Space Technology Mission (STMD) Game Changing Development (GCD) Program.

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CraterGrader: Autonomous Planning and Control For Leveling Unstructured Lunar Terrain

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Introduction: U.S. interest in a sustained presence on the Lunar surface necessitates technologies for preparing and maintaining infrastructure in hostile and remote environments. Significant worksite preparation and leveling is a prerequisite for building and maintaining the landing pads, roads, and foundations for such presence. Contemporary terrestrial grading relies on discretion and experience of highly trained operators to move earth, which does not extend to fully remote, 300-hour continuous operation in alien environments. Earth-based automation enabled approaches leverage brute force and massive energetics, unavailable in Lunar environments, and use basic levels of localization and control.

Sitewide autonomy planners for grading vehicles outside of simulation have yet to be developed in a meaningful way in SOA, and the Lunar environment imposed mass and localization constraints further constrain the problem. The work herein addresses aforementioned pain points by developing a novel terrain understanding and planning worksystem for autonomous manipulation of deformable terrain, coining and abiding by the term “patient work”, to level terrain slowly but robustly and optimally for long periods under minimal-to-no supervision.

Methodology: The approach described in this abstract, referred to as CraterGrader, leverages priors in robotics and SOA earthmoving automation-enabled techniques. CraterGrader is an autonomy and sensing suite built upon a flight-facing worksystem comprising of a mobility platform and a quiver of tools. The system is in development at Carnegie Mellon University’s Robotics Institute, being tested in a 600 square foot “moonyard”; stocked with Lunar-like simulants that are tunable for specific surface morphologies. The moonyard is equipped with motion capture and laser scanning technology for ground truth of vehicle localization and worksite topography. The technical crux boils down to robust 3D pose estimation with limited sensing modalities and external infrastructure, mapping changing terrain, and planning how to manipulate terrain to flatten and prepare a worksite.

Results: The backbone of CraterGrader’s pose estimation comes from time-of-flight positioning sensors placed at worksite initialization, in combination with traditional sensor fusion, visual odometry, and SLAM techniques for online scene understanding. The proposed approach generalizes to any robotic vehicle attempting to operate in a high slip, millimeter precision environment and can be adapted to work vehicles for the Lunar surface which may be designed to: compact, load, haul, 3D print, or trench.

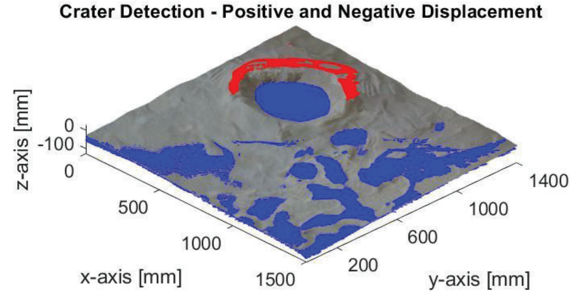

Figure 1. CraterGrader Lunar Site Map

Terrain sensing is manifested as stereo correspondence in the visual spectrum. Point clouds are handled onboard in real time, filtered, and combined into a semantic feature representation of the worksite. This semantic map consists of labeled deviations from the desired worksite plane and contains information about location and volumetric displacement.

The planner leverages terrain topography features to generate skill and motion primitives that achieve time and energy-efficient terrain manipulation. The architecture is centered on a nodal cost map encoding volume, shape, and location of local optimums. The worksite is decomposed into a hybrid configuration space to capture variable planning and motion constraints. The planner uses the earth mover’s distance metric to optimally plan node manipulation subject to configuration space constraints. These plans are then converted to preferential skill primitives that range in complexity depending on terrain detection certainty and complexity. A transition model is used as a heuristic for manipulated material until the terrain is again sensed and fused by the perception subsystem.

Conclusions: Establishment of sustained Lunar presence will require robust in-situ autonomous construction worksystems, central to which are terrain understanding and planning algorithms as presented in this work. Insights gained from the proposed algorithms may illuminate terrestrial construction planning methods and may push SOA in multiple domains.

The Kinematic Navigation and Cartography Knapsack (KNaCK) LiDAR System. M. Zanetti[1], B. Robinson[2], P. Bremner[1], K. Miller[1], B. De Leon Santiago[1], E. Hayward[1], J. Jetton[2], [1]NASA Marshall Space Flight Center, Huntsville, AL 35805, [2]Torch-Technologies, Inc, Huntsville. (Michael.R.Zanetti@nasa.gov).

Introduction: Improved terrain characterization and navigation sensors are needed to enhance crew safety, ISRU return, and scientific understanding of future lunar landing sites. Specific to the Artemis Program and sustained exploration at the lunar South Pole, are extreme illumination conditions that will hamper existing photogrammetry-based robotic navigation. Additionally, a major challenge for navigation on the Moon and other planetary surfaces is the lack of Global Positioning and Navigation Systems (GPS/GNSS). Thus, there is a need for an alternative to camera-based navigation that allows for precise and accurate mapping in GPS-denied environments on any planetary body.

The Kinematic Navigation and Cartography Knapsack (KNaCK) LiDAR system is a 2020 NASA STMD Early Career Initiative (ECI) project with the aim of assessing how Velocity-Sensing FMCW-LiDAR sensors and mobile LiDAR con-ops can address challenges in lunar terrain mapping and navigation at the Moon's South Pole, and to advance the TRL of commercial prototype FMCW-LiDAR sensors for extreme-environments and the lunar surface.

The Kinematic Navigation and Cartography Knapsack (KNaCK) LiDAR instrument: The KNaCK is a backpack-mounted, mobile navigation and terrain mapping system that uses scanning *velocity-sensing* coherent light detection and ranging (LiDAR) system based on a frequency modulated continuous wave (FMCW) technique. FMCW-LiDAR is immune to direct solar interference (and other LiDAR sources), with a solid-state LIDAR-on-a-chip architecture with minimal moving parts. The test-article is equipped with FMCW-LIDAR, a time-of-flight LiDAR, 3 inertial measurement units (IMU), GPS, and on-board computing and power. During a traverse, the sensors continually scan the environment to build a three-dimensional point cloud representation of topography, as well as providing real-time mapping and hazard avoidance for rover navigation. The system is modular and is also fitted to a small rover platform for research into autonomous rover mapping.

SLAM Algorithm Development: The KNaCK Project is also developing novel simultaneous localization and mapping (SLAM) algorithms based on the unique velocity data available from FMCW-LiDAR. The concurrent range and velocity

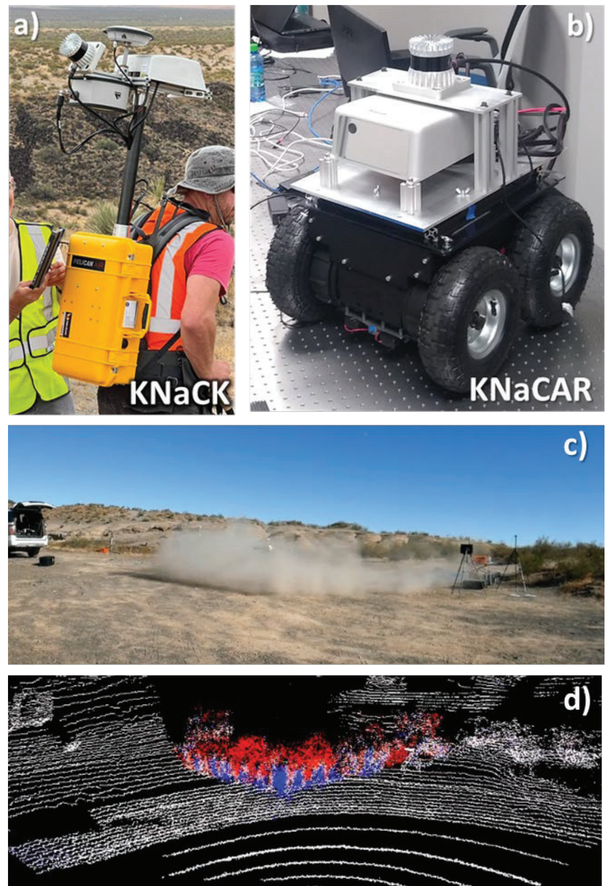

Figure 1: a) The KNaCK backpack mobile LIDAR scanning system in the field in NM. b) The KNaCK autonomous rover platform. c) HD video of a UAV quadcopter drone landing, creating a dust cloud. d) doppler shift (red away, blue toward sensor) instantaneous velocity of lofted dust particles by the UAV. A rotational vortex is visible in real-time data playback

information sampled at each of 10^6 points/sec allow for measurement of ego-motion odometry, improved spatial state estimation, and iterative-feedback algorithms to constrain IMU bias propagation errors. These solutions allow cm-scale accurate mapping in GPS-denied environments with respectable (dm-scale) loop-closed scan matching spatial error. Results from field testing and planetary analog science at NASA KSC and SSERVI RISE2 Kilbourne Hole, NM will be presented.

Environmental Testing: Thermal, vacuum, and radiation testing of an FMCW-LiDAR chipset is scheduled for late June 2022.

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