Lunar Surface Innovation

CONSORTIUM

SPRING MEETING

APRIL 23-25, 2024

JOHNS HOPKINS
APPLIED PHYSICS 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 (STMD) under the Lunar Surface Innovation Initiative (LSII). LSIC fosters communications and collaborations among academia, industry, and Government. Members have expertise in LSII key capability areas.

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

AGENDA

DAY 1, Tuesday, April 23, 2024

All times are Eastern Daylight Time.

9:00 AM	Coffee, Networking, and Registration in Person	
10:00 AM	Welcome and Logistics	Jamie Porter, LSIC Director, JHU/APL Bobby Braun, Space Sector Head, JHU/APL
10:15 AM	NASA Welcome	Jim Free, Associate Administrator, NASA (recorded message)
10:20 AM	Keynote	**Kurt "Spuds" Vogel,** Associate Administrator for Space Technology, NASA
10:45 AM	Break	
11:00 AM	Moon to Mars Architecture	**MODERATOR:** Niki Werkheiser, Director of Technology Maturation and Lunar Surface Innovation Initiative (LSII) Lead, NASA Space Technology Mission Directorate (STMD) **PANELISTS:** **NASA Space Technology Mission Directorate (STMD)** Walt Engelund, Deputy Associate Administrator for Programs **NASA Exploration Systems Development Mission Directorate (ESDMD)** Nujoud Merancy, Deputy Associate Administrator for Strategy and Architecture **NASA Science Mission Directorate (SMD)** Joel Kearns, Deputy Associate Administrator for Exploration **NASA Space Operations Mission Directorate (SOMD)** Pat Forrester, Advisor
12:15 PM	Lunch Break	Rooms 130 and 131**: *Invite Only* —** Student Lunch With Senior Leaders Room 128: In Situ Resource Utilization Networking Room 127: Surface Power Networking Room 126: Excavation and Construction Networking Rooms 124 and 125: Crosscutting Capabilities Networking

AGENDA CONTINUED

DAY 1, Tuesday, April 23, 2024

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1:45 PM	LSII Updates	Niki Werkheiser, Director of Technology Maturation and LSII Lead, NASA STMD
2:00 PM	LSII and LSIC Updates	**LSII** Wes Fuhrman, LSII Lead, JHU/APL **LSIC** Jamie Porter, LSIC Director, JHU/APL **Excavation and Construction** Jibu Abraham, JHU/APL **In Situ Resource Utilization** Jodi Berdis, JHU/APL **Surface Power** Samantha Andrade, JHU/APL **Crosscutting Technologies** Danielle Mortensen, JHU/APL
2:30 PM	Working Group Breakout Sessions	Rooms 124 and 125: In Situ Resource Utilization Rooms 126 and 127: Surface Power Rooms 128 and 129: Excavation and Construction Rooms 130 and 131: Crosscutting Capabilities
3:15 PM	Break	
3:30 PM	Lunar Surface Technology Research (LuSTR) 2021 Presentations	**MODERATOR**: Harri Vanhala, LuSTR Lead, NASA STMD **PANELISTS:** **Autonomous Site Preparation: Excavation, Compaction, and Testing (ASPECT)** Christopher Dreyer, Colorado School of Mines **Regolith Beneficiation System for Production of Lunar Calcium and Aluminum** Daoru Han, Missouri University of Science and Technology **Cold-Tolerant Electronics and Packaging for Lunar Surface Exploration** Michael Hamilton, Virtual, Auburn University
4:30 PM	Lightning Talks	
5:30 PM	Poster Session and Networking	
6:30 PM	Closing and Adjourn for the Day	

AGENDA CONTINUED

DAY 2, Wednesday, April 24, 2024

All times are Eastern Daylight Time.

9:00 AM	Coffee, Networking, and Registration in Person	
10:00 AM	Welcome and Logistics	Karen Stockstill-Cahill, LSIC Deputy Director, JHU/APL Laura Cosentino, LSII Program Manager, JHU/APL
10:05 AM	What We Do to Get to the Moon Together	**MODERATOR**: Erica Rodgers, Director of Advanced Programs, OTPS **PANELISTS:** **IM-1** Ben Bussey, Chief Scientist, Intuitive Machines **Peregrine Mission One** Dan Hendrickson, Vice President of Business Development, Astrobotic **Blue Ghost Mission 1** Joseph Marlin, Deputy Chief Engineer, Firefly
11:10 AM	Break	
11:25 AM	How We Get to the Moon Together	**MODERATOR**: Rachel Klima, Lunar Technology and Science Advisor, JHU/APL **PANELISTS:** **US Technology Policy and Strategy** Jonny Pellish, Director of Civil Space Policy National Space Council (NSpC) **International Lunar Year** David Reinecke, Foreign Affairs Officer, U.S. Department of State **Artemis Accords** Kent Bress, Director of Aeronautics and Cross-Agency Support Division, Office of International and Interagency Relations, NASA **International Perspective** Masami Onoda, Director of JAXA, Washington D.C. Office **Commercial Perspective** Stephen Indyk, Director of Space Systems, Honeybee Robotics, and Lunar Exploration Analysis Group (LEAG) Commercial Advisory Board (CAB) Chair
12:55 PM	Lunch	
1:15 PM	Dining Room	STMD Lunch & Learn: Technology Shortfall Feedback & Prioritization Process with Spuds Vogel and Alesyn Lowry, Director of Strategic Planning and Integration, NASA STMD The LSIC keynote introduced NASA's strategy for establishing national tech base priorities. Join us to learn more about the process underway to collect feedback about technology shortfalls based on stakeholders' prioritized needs (including yours!). STMD will show the initial shortfall list and descriptions, discuss desired feedback, and answer questions.

AGENDA CONTINUED

DAY 2, Wednesday, April 24, 2024

All times are Eastern Daylight Time.

2:30 PM	Technology Showcase	**MODERATOR**: Betsy Congdon, LSII Chief Technologist, JHU/APL **PANELISTS:** **Cooperative Autonomous Distributed Robotic Exploration (CADRE)** Subha Comandur, CADRE Project Manager **ISRU Pilot Excavator (IPEx)** Jason Schuler, IPEx Project Manager **Polar Resources Ice Mining Experiment (PRIME-1)** Jackie Quinn, PRIME Project Manager **Moon to Mars Planetary Autonomous Construction Technology (MMPACT)** Evan Jensen, Vice President of Strategic R&D, ICON Technology Inc. **Lunar Relay Satellites:** Mehak Sarang, ispace – U.S. Payloads Manager **AstroVinci** Peter Frye, Space Applications Manager, Westinghouse
4:30 PM	Technology Show and Tell and Networking (*Technologies listed on page 14.*)	
6:00 PM	Closing and Adjourn for the Day	

AGENDA CONTINUED

DAY 3, Thursday, April 25, 2024

All times are Eastern Daylight Time.

9:00 AM	Coffee, Networking, and Registration in Person	
10:00 AM	Welcome and Logistics	Jamie Porter, LSIC Director, JHU/APL Dan Meidenbauer, LSII Deputy Program Manager, JHU/APL
10:05 AM	Keynote	Phil Root, Director, Strategic Technology Office, DARPA
10:25 AM	LunA-10 Initial Results	**Overview of LunA-10** Michael Nayak, LunA-10 and LOGIC Program Manager, DARPA **Overview of LunA-10 Results** Shawn Britton, Liaison to DARPA LunA-10 Government Integration Team, NASA Elizabeth Hyde, U.S. Geological Survey (USGS) **Summary of Open Questions** Phil Root and Michael "Orbit" Nayak, DARPA
11:25 AM	Break	

11:35 AM	Concurrent Breakout Sessions:	
Room	Breakout Session, 11:35 AM – 12:15 PM	Breakout Session, 12:20 – 1:00 PM
Auditorium	Inclusion Strategies for NASA Solicitations	Inclusion Strategies for NASA Solicitations
Dining Area	LSII/LSIC Coordination With Other Stakeholders	LSII/LSIC Coordination With Other Stakeholders
Rooms 124 and 125	International Collaborations	International Collaborations
Rooms 126 and 127	Deconfliction of Space Activities	Deconfliction of Space Activities
Rooms 128 and 129	DARPA LunA-10 Performer Results for Construction, Robotics, ISRU, Transportation Logistics	Avionics, Autonomy, and Robotics Tradespace
Rooms 130 and 131	DARPA LunA-10 Performer Results for Power, Communications/Navigation/PNT	DARPA Roundtable Discussion on LunA-10

(See breakout descriptions on the next page.)

1:00 PM	Closing and Adjourn for the Day

AGENDA CONTINUED

DAY 3, Thursday, April 25, 2024

All times are Eastern Daylight Time.

BREAKOUT DESCRIPTIONS

Topic: Inclusion Strategies for NASA Solicitations
POCs: Denna Lambert, Christa Jensen, Angela Dapremont

- Collaborative conversation on the best practices and strategies to nurture and advance new entrants into NASA's space ecosystem, creating opportunities to meet innovators where they are and to be logical and responsive to the needs of diverse communities.
- Open dialogue that will highlight benchmarking research done across the federal government and insights gained from program and Center-level interventions employed in recent solicitation cycles, and that creates a space for knowledge sharing with LSIC participants.
- Open the conversation to share lived experiences that will assist STMD in creating adaptable and responsive solicitations that drive and promote technological solutions across the ecosystem.

Topic: LSII/LSIC Coordination With Other Stakeholders
POCs: Karen Stockstill-Cahill, Danielle Mortensen, Ben Greenhagen, Kristin Jaburek

- Discuss areas of overlap and divergence between topics covered and solutions developed by LSIC and other stakeholder groups.
- Explore how LSIC and other stakeholder groups might coordinate to ensure complementary efforts that maximize outcomes and utility to the community.

Topic: International Collaborations
POCs: Rachel Klima, Josh Cahill, David Reinecke, Tim Cichan

- Discuss opportunities for and barriers to international collaboration on technology development.
- Introduce the International Lunar Year 2027 (ILY2027).
- Discuss how technology developers can support and benefit from ILY2027.

Topic: Deconfliction of Space Activities
POCs: Therese Jones, Samantha Andrade

The purpose of this breakout session is to take the first steps toward addressing the need to determine how to deconflict lunar activities as countries and private sector companies plan to establish lunar operations. It will:

- Seek feedback to determine the breadth of interference concerns.
- Clarify community usage of the terms "interference," "contamination," and "deconfliction."
- Aims to contribute to the development of a framework for further deconfliction activity.

Topic: DARPA: LunA-10 Performer Results for Construction, Robotics, ISRU, Transportation Logistics
POCs: Ashley Batjer, Lee Pele, Jibu Abraham

- Enable LunA-10 performers to share posters on display and personnel on-site to provide background information and answer questions on their systems
- Provide an opportunity for the LSIC community to see system details for key components behind the LunA-10 frameworks

Topic: Avionics, Autonomy, and Robotics Tradespace
POCs: Wes Powell, Danette Allen, Josh Mehling, Jibu Abraham

The purpose of this breakout session is to take the first steps toward addressing this need. It will:

- Understand the needs and interests for the Avionics, Autonomy, and Robotics Tradespace within LSIC.
- Identify people interested in establishing a community to address this need.
- Survey any relevant ongoing "conversations" and work.
- Define a forward path to address this need, which may include virtual community meetings, additional workshops, etc.

Topic: DARPA: LunA-10 Performer Results for Power, Communications/Navigation/PNT
POCs: Christie White, Lee Pele, Wes Fuhrman

- Enable LunA-10 performers to share posters on display and personnel on-site to provide background information and answer questions on their systems.
- Provide an opportunity for the LSIC community to see system details for key components behind the LunA-10 frameworks.

Topic: DARPA: Roundtable Discussion on LunA-10
POCs: Christie White, Ashley Batjer, Lee Pele, Wes Fuhrman

- Conduct a DARPA workshop to collect community feedback on the LunA-10 frameworks.
- Background reading and discussion topics/questions will be provided for advance review.

Bobby Braun

JHU/APL

Dr. Robert D. Braun is head of the Space Exploration Sector at the Johns Hopkins Applied Physics Laboratory (APL), with responsibilities that span all civil and national security space activities at the Lab. He has contributed to the formulation, development, and operation of multiple spaceflight missions and is a recognized authority in hypersonics technology and the development of entry, descent, and landing systems. Dr. Braun previously served in executive positions at the Jet Propulsion Laboratory, the University of Colorado Boulder (CU Boulder), and NASA, and has served as a tenured professor at Georgia Tech, CU Boulder, and Caltech. He earned a B.S. in aerospace engineering from Pennsylvania State University, an M.S. in astronautics from George Washington University, and a Ph.D. in aeronautics and astronautics from Stanford University. He is a member of the National Academy of Engineering, a fellow of the American Institute of Aeronautics and Astronautics and the American Astronomical Society, and the author or coauthor of over 300 technical publications.

Kent Bress

NASA

Kent Bress is the director of the Aeronautics and Cross Agency Support Division in the Office of International and Interagency Relations (OIIR) at NASA Headquarters in Washington, DC. He has served in that office since 1993, and has been a division director in it since 2007. In his current position he oversees NASA's collaboration with Europe and Canada, and supervises the negotiation of international agreements in the areas of aeronautics, space technology, education and public outreach. From 1997 until 1999 he was NASA's representative in Moscow, Russia.

Kent began his career at NASA as a Presidential Management Intern (Fellow) in 1990, after studying Russian and German at the University of Iowa and receiving a Master's Degree in Foreign Affairs from the University of Virginia. He earned his MBA from Georgetown in 2001.

Shawn R. Britton

DARPA

Shawn Britton currently serves as a NASA liaison to the DARPA LunA-10 Government Integration Team (GIT) supporting efforts to develop a commercial lunar surface technical framework for the early 2030s. He is the Associate Director for Data Systems for the Research Directorate (RD) at NASA's Langley Research Center responsible for oversight of hardware and software aspects of RD's portfolio of Data Acquisition capabilities for large scale testing facilities. Additionally, Shawn is the assistant branch head for the Advanced Measurement and Data Systems branch at Langley. Prior to his tenure in RD, Shawn was a member of the Game Changing Development (GCD) Program Office in the Space Technology Mission Directorate (STMD) as a Program Element Manager where he managed a portfolio of technology maturation projects from across the Agency and JPL, focusing on Robotics, OSAM, Large Scale Excavation and Construction, Nuclear Thermal Propulsion and Extreme Environment survivability. Shawn additionally served as the Lead for the Digital Operations and Transformation (DOT) Team within GCD responsible for GCD's digital presence and data and analytics efforts. Shawn began his NASA career as Metrology and Calibration Program Manager and Standard Practice Engineer for Langley, providing center guidance and insight for international and industry measurement controls and standards.

Prior to NASA, Shawn served as the lead technical manager for the Test Measurement and Diagnostic (TMDE) Metrology Laboratory at Aberdeen Proving Ground in Aberdeen, MD, a Nuclear Design Engineer on Primary Loop Reactor Components and Systems for Los Angeles (SSN688) Class Submarines at Pearl Harbor Naval Shipyard in Honolulu, HI and the Lead Test Engineer on Steering Systems for Nimitz-Class Carriers (CVN) for Newport News Shipbuilding in Newport News, VA. He holds a M.S. in Mechanical Engineering from the University of Hawaiʻi Mānoa in Honolulu, HI and a B.S. in Mechanical Engineering from the Pennsylvania State University in University Park, PA. Shawn is the recipient of a NASA Exceptional Achievement Award, two NASA Group Achievement Awards and the STMD Outstanding Performance Award. In his spare time, Shawn enjoys spending time with his family of three creative kids, a wonderful wife and two spoiled dogs.

Ben Bussey, PhD.

Intuitive Machines

Dr. Bussey is a planetary scientist who is currently the chief scientist for Intuitive Machines. 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 during his 20 years at the Johns Hopkins University Applied Physics Laboratory, before joining Intuitive Machines in 2022. He has also worked at the Lunar and Planetary Institute in Houston, the European Space Agency, Northwestern University and the University of Hawaii.

Dr. 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 spent 5-years at NASA HQ which included roles as the Acting Deputy Associate Administrator of Exploration in NASA's Science Mission Directorate, and as the Chief Exploration Scientist in the Human Exploration and Operations Mission Directorate. During his time at JHU/APL he was Principal Investigator of NASA VORTICES SSERVI and NASA Lunar Science Institute research teams 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.

Subha Comandur

Jet Propulsion Laboratory

Subha Comandur is currently Project Manager of CADRE, a robotics technology demonstration lunar mission at the Jet Propulsion Lab in Pasadena, CA. She has over twenty years of engineering, project & people leadership experience at JPL and Industry on various spacecraft missions including Europa Clipper, Mars Curiosity Rover, JUNO, and Soil Moisture Active Passive (SMAP). Subha has earned various awards including a NASA honor medal for Early Career Achievement in 2014, JPL award for Exceptional People Leadership in 2017 and a Principal Designation in 2019. Prior to CADRE, Subha led a large, multidisciplinary team as the Product Delivery Manager for Mechanical and Harness Subsystems on Europa Clipper spacecraft. Subha started her career at Boeing as an electrical engineer, where she worked on numerous projects including demonstration of on-orbit autonomous servicing spacecraft. She has a Masters in Computer Science from University of California, Irvine and a Bachelors in Electrical and Electronics Engineering from India.

Chris Dryer

Colorado School of Mines

Dr. Dreyer earned a B.S. in Mechanical Engineering from Drexel University and M.S. and PhD in Mechanical Engineering from the University of Colorado Boulder in 2020. He joined the Colorado School of Mines in 2000 as a Research Professor and developed an independent research program focused on instrumentation for energy systems, instrumentation for space exploration and space resource technology development. He is a Professor of Practice in the Space Resources Graduate Program (space.mines.edu), the first educational program in the world dedicated to teaching space resource development, which he co-founded in 2018. Dr. Dreyer is the Director of Engineering in the Center for Space Resources at CSM, in which he guides the experimental research direction of the center. He has developed experimental facilities for resource technology development including, prospecting instruments, resource extraction, surface property measurement, and resource processing. He has served as the Chair of the AIAA Space Resources Technical Committee and leadership positions in the ASCE Aerospace Division.

Walt Engelund

NASA

Walter (Walt) Engelund serves as the Deputy Associate Administrator for Programs in the Space Technology Mission Directorate (STMD) at NASA Headquarters and provides executive leadership and execution for a portfolio of 10 space technology programs with an annual investment value of over $1 billion. STMD invests in technologies for NASA and commercial space needs that span the full range of technology readiness levels (TRLs), from fundamental laboratory experiments to full scale space flight demonstrations.

Prior to his appointment with STMD in 2019, Engelund spent 30 years at NASA's Langley Research Center in Hampton, Virginia, 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. He also previously served as the Chief Engineer at NASA Langley 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 is a Fellow in the American Institute of Aeronautics and Astronautics (AIAA), and the recipient of numerous NASA Achievement Awards including NASA's Exceptional Engineering Achievement and the Exceptional Achievement Medals, and the Meritorious Presidential Executive Award.

Pat Forrester

NASA

Pat Forrester serves as an advisor to the Associate Administrator for Space Operations and as the director of Cross-Directorate Technical Integration at NASA Headquarters in Washington, D.C. Prior to his current assignment, he was the chief of the Astronaut Office. He was selected as an astronaut by NASA in 1996 and flew on three space shuttle missions to the International Space Station.

Prior to joining NASA, Pat served in the United States Army as an operational aviator and test pilot. He retired from the Army in 2005 and was inducted into the U.S. Army Aviation Hall of Fame in 2011.

Pat received a Bachelor of Science Degree in Applied Sciences and Engineering from the United States Military Academy, West Point, New York, in 1979, and a Master of Science Degree in Mechanical and Aerospace Engineering from the University of Virginia in 1989. His military schools include the Army Parachutist Course, U.S. Army Ranger School, and the Command and General Staff College.

Peter Frye

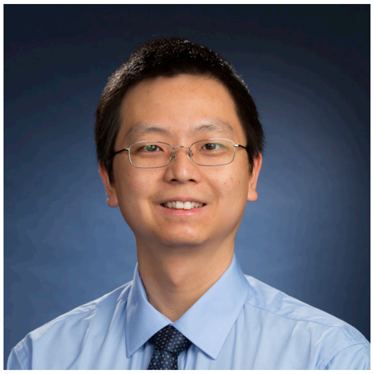
Westinghouse

Pete leads the development of nuclear reactors tailored for space at Westinghouse. Prior to joining, he has previously led development efforts on lunar landers, satellites, aircraft, helicopters & other robotic systems. He has spent time at Boeing, GE Aerospace, and Astrobotic. He has multiple patents and publications and holds both a BS & MS in Mechanical Engineering from Drexel University.

Michael Hamilton

Auburn University

Dr. Michael C. Hamilton obtained his B.S.E.E. from Auburn University in 2000 and M.S.E.E. and Ph.D. from The University of Michigan in 2003 and 2005, respectively. From 2006 to 2010, he was at MIT-Lincoln Laboratory, where he worked on a range of microwave and solid-state device, as well as system-level, projects. Dr. Hamilton joined the Electrical and Computer Engineering Department of Auburn University as an Assistant Professor in 2010 and is now James B. Davis Professor. In 2016, he became the Director of the Alabama Micro/Nano Science and Technology Center (AMNSTC), which is a micro/nano technology center at Auburn University funded by the State of AL. He is also currently leading wiring and packaging efforts in the Google Quantum AI group, which is working to realize useful, scalable quantum computing technologies.



Daoru (Frank) Han

Associate Professor of Aerospace Engineering
Director, Gas and Plasma Dynamics Laboratory
Missouri University of Science and Technology (Missouri S&T)

Dr. Han received his PhD in Astronautical Engineering from University of Southern California (USC) in 2015. From 2016 to 2017 he was an Assistant Research Professor at Worcester Polytechnic Institute (WPI). He joined Missouri S&T in 2017 where he is currently an Associate Professor of Aerospace Engineering and Director of the Gas and Plasma Dynamics Laboratory which houses a large (6-ft diameter, 10-ft long) thermal-vacuum-plasma chamber to simulate space environments leveraging his modeling/computing expertise. At Missouri S&T, his research efforts include 1) development of particle-based kinetic models for particulates in fluids and plasmas, 2) ground testing of ion sources simulating interplanetary solar wind and LEO plasma environments, and 3) advanced space propulsion modeling. Recent accolades of Dr. Han include the Bernard Ray Hawke Next Lunar Generation Career Development Award from LEAG (supported by NASA) in 2019, the Young Investigator Award (YIP) from the AFOSR in 2021, and Dean's Scholar for AY 2022-2024 at Missouri S&T.

Dan Hendrickson

Astrobotic

Dan Hendrickson serves as the Vice President of Business Development for Astrobotic, a lunar logistics company based in Pittsburgh, Pennsylvania. Dan leads the company's lunar and space robotics sales efforts across the company. Prior to Astrobotic, Dan served as the Director of Civil and Commercial Space Systems at the Aerospace Industries Association (AIA).

Elizabeth (Liz) Hyde

USGS

Elizabeth (Liz) Hyde started as a founding member of the UAS Research Center at the USGS in July 2020. As one of the few hardware engineers in the Survey, her role is to enable scientific exploration and operations by designing, building, testing, and flying new and novel instruments on a variety of aircraft and robotic platforms. Her projects cover all five of the USGS Mission Areas; from integrating new telemetry sensors on sUAS, to installing low-overhead hyperspectral imagers on stratospheric aircraft; from developing new technologies to track endangered species, to improving hydrological measurements by developing UAS-based non-contract stream gaging methods; and integrating sensitive magnetometers and ground-penetrating radars on new vehicles to aid in the search for critical minerals in previously inaccessible areas.

Prior to joining the Survey, Liz worked in various Mechanical and Systems Engineering contract roles at NASA Ames Research Center. She was a mechanical and systems engineer on a variety of small satellite projects, including acting as a Lead SME for a series of Artemis I CubeSats; designed and certified science instruments for deployment on aircraft ranging from the SIERRA-B UAS to SOFIA (a Boeing 747-SP); designed and built fluidics experiments bound for the ISS, and tested them in microgravity on Zero-G parabolic flights. She also volunteered and deployed as a communications specialist on a FEMA Urban Search and Rescue Task Force, worked as a Rescue Tech on the NASA Ames Disaster Assistance and Rescue Team, and was a certified EMT. She is also a Private Pilot, and an Amateur Radio operator. She holds a M.S. and B.S. in Aerospace Engineering from San Jose State University.

Stephen Indyk

Honeybee Robotics

Stephen Indyk is the Director of Space Systems at Honeybee Robotics, in Greenbelt, Maryland. He has been with the company since 2011 after receiving a M.S. & B.S. in Mechanical Engineering from Rutgers University. During this time, he has lead flight hardware sampling system development projects destined for Mars, the Moon, and Saturn's moon Titan. This includes missions such as Mars Sample Return (MSR), Commercial Lunar Payloads Services (CLPS), & Dragonfly. He is a member of the science teams for both the Mars Science Laboratory rover, Curiosity, and the Mars Exploration Rovers, Sprit and Opportunity. Flight operation instrument experience have included the Sample Analysis on Mars (SAM) and the Rock Abrasion Tool (RAT). Stephen also the Commercial Advisory Board chair (CAB) for the Lunar Exploration Analysis Group (LEAG) and also leads the Lunar Surface Innovation Consortium (LSIC) Crosscutting Capabilities for Vacuum Environment, engaging and expanding NASAs lunar research communities understanding of the difficulties in engineering systems for the lunar environment. Additional research interests include planetary in-situ resource utilization technologies and mechanisms for extreme environments.

Evan Jensen

Vice President
Strategic R&D

Evan leads ICON's Strategic R&D programs. As ICON's 11th employee, he was responsible for the system and software architectures of ICON's Vulcan series of additive construction systems, and ICON's additive construction system for the Lunar surface. Evan has been in the field of robotics, mechatronics, and technology development for over 20 years. His core competencies in systems integration and strategic partnerships will help solve the complex challenges of additive construction at scale, terrestrially and now in space leading ICON's Project Olympus. Evan holds an MS in Science and Technology, Texas State University.

Joel Kearns

Deputy Associate Administrator for Exploration,
NASA SMD

Dr. Joel Kearns is the Deputy Associate Administrator for Exploration in NASA's Science Mission Directorate. He leads the Exploration Science Strategy and Integration Office and the Lunar Discovery and Exploration Program, including the Commercial Lunar Payload Services initiative. Kearns leads science planning associated with human exploration beyond low Earth Orbit, and integration with NASA's exploration systems development, space technology and space operations mission directorates.

Prior to this assignment, Dr. Kearns served as Director for Facilities, Test and Manufacturing at Glenn Research Center in Cleveland, Ohio; earlier he was Deputy Director of Glenn's Space Flight Systems Directorate and Manager of the Orion Program's European Service Module Integration Office. He was Space Shuttle Transition and Retirement Manager at NASA Headquarters, Director of Project Management and Engineering at Ames Research Center, Program Manager of the Stratospheric Observatory for Infrared Astronomy at Ames, Program Manager of Microgravity Research during the Space Shuttle Spacelab and Mir era, at Marshall Space Flight Center, and Program Manager for Microgravity Materials Science and Biotechnology at NASA Headquarters.

A materials scientist, his research interests include phase transformations, solidification, single crystal growth, defects in semiconductor silicon, electron microscopy and spectroscopy and x-ray diffraction. His work focused on growth and defect engineering of dislocation free bulk silicon optimized for power semiconductor or photovoltaic devices.

Dr. Kearns was born in Massachusetts. He graduated with a BS and MS in Mechanical Engineering, and a PhD in Materials Science and Engineering, from Worcester Polytechnic Institute. Kearns earned a graduate certificate in Advanced Materials Characterization from University of Connecticut's Institute of Materials Science, and a graduate certificate in Nanoscale Materials Science from Stanford University. He also completed a professional certificate in Energy Innovation and Emerging Technologies from Stanford University. He was Director of Crystal Technology and Vice President for Engineering and Technology at SUMCO USA and Vice President for Solar R&D at MEMC Electronic Materials. He worked at Grumman Aerospace and the Mitre Corporation. Dr. Kearns is an associate fellow of the American Institute for Aeronautics and Astronautics. Kearns was awarded the U.S. Government's Presidential Rank of Meritorious Senior Executive in 2009. He is an inventor on four patents for single crystal growth technology.

Joseph Marlin

Firefly Aerospace

Joseph Marlin serves as the Deputy Chief Engineer of the Blue Ghost lunar program at Firefly Aerospace. Prior to this role, he led avionics design and test for the Blue Ghost lunar lander, and electrical ground support equipment design and build-out at the company's Vandenberg Space Force Base launch site.

Nujoud Merancy

NASA

Nujoud Merancy is the   for the Strategy & Architecture Office (SAO) in the Exploration Systems Development Mission Directorate (ESDMD) for NASA Headquarters. Based at NASA's Johnson Space Center in Houston, Merancy serves as the agency expert in exploration architectures, guiding technical aspects of agency decisions about exploration element-level performance and functionality, which will have decades-long implications for agency goals and international and commercial partnerships. She oversees the annual Architecture Concept Review cycle, in which NASA refines the exploration architecture that guides its efforts to return astronauts to the Moon, establish an ongoing lunar presence, and land humans on Mars.

Prior to her current role, Merancy served as the architecture integration manager within SAO. Before joining ESDMD, she served as the chief of the Exploration Mission Planning Division within the Exploration Architecture, Integration, and Science Directorate; led the Mission Analysis and Integrated Assessments team; and held various roles supporting Orion Program mission planning and analysis, all at Johnson Space Center. She began her career working in industry supporting early International Space Station development and operations.

Merancy holds a Bachelor of Science in Aeronautical and Astronautical Engineering from the University of Washington and a Master of Science in Systems Engineering from the University of Houston–Clear Lake.? She is a recipient of a NASA Exceptional Public Service Medal, Rotary National Award for Space Achievement Stellar Team Award, and the Silver Snoopy, an award that NASA astronauts bestow for outstanding contributions to flight safety, for designing the space station's loss of attitude control warning.

Michael (Orbit) Nayak

DARPA

Dr. Michael "Orbit" Nayak (Maj, USAF) joined DARPA as a program manager in May 2022. At DARPA, he is interested in inventive ways to apply techniques from the disciplines of astrophysics and planetary science to problems in space domain awareness (SDA), space control, very bright and compact X-ray imaging sources for medical and aerospace imaging, and preventing strategic surprise in cislunar space. His research interests include methods to remotely identify characteristic satellite frequencies, radically innovative solutions to modern optical detection problems, cutting-edge nanosatellite mission concepts, and problems facing the rapid proliferation of people and materials on the lunar surface.

Prior to DARPA, Nayak worked as a space shuttle engineer; flight director for multiple experimental spacecraft; a skydiving instructor; a planetary scientist at NASA Ames; research section chief for the DoD's largest telescope; instructor flight test engineer and instructor pilot. He has flown an X-plane, worked flight test for the prototype T-7A trainer jet, deployed to the South Pole as a U.S. Antarctic Program principal investigator, managed air- and space-based special programs, and was a semi-finalist for the 2021 astronaut class. He is a USAF Test Pilot School graduate, Rotary National Award for Space Achievement recipient, and has 1,000+ hours of flight time in 40+ aircraft including the F-16, T-38, EA500 and BE-76.

He holds a doctorate degree in planetary science from the University of California at Santa Cruz, where he was a National Defense Science and Engineering Graduate Fellow. He holds additional graduate degrees in earth science, aerospace engineering and flight test engineering.

Masami Onoda

JAXA

Masami Onoda is currently Director of JAXA Washington D.C. Office, representing the Japanese space agency in the Americas. Dr. Onoda has extensive experience in international affairs, satellite applications and industry relations. She has held several international positions, including at the intergovernmental Group on Earth Observations (GEO) Secretariat in Geneva, Switzerland, and at the UN Office for Outer Space Affairs in Vienna, Austria. She worked with Small and Medium size Enterprises on small satellite technology transfer while operating the JAXA office in Osaka, Japan. Dr. Onoda holds a Ph.D. in Global Environmental Studies (2009) and master's degree in environmental management (2005), both from Kyoto University Graduate School of Global Environmental Studies, and a BA in international relations from the University of Tokyo.

Jackie Quinn

NASA

For over 30 years, Jackie Quinn has worked for NASA at the Kennedy Space Center. She was involved with groundwater cleanup at the space center for more than a decade before returning to the laboratory for environmental and lunar focused research and development initiatives. Her educational background includes a Bachelor's in civil engineering (1989, Georgia Institute of Technology), a Master of Science in Environmental Engineering (1994, University of Central Florida), and a Doctorate in Environmental Engineering (1999, University of Central Florida). Dr. Quinn has published in peer-review journals and presented at numerous technical conferences. She is an inductee in the Space Technology Hall of Fame and is the recipient of both NASA's Government and Commercial Invention of the Year Awards. Dr. Quinn was inducted in 2016 into the Florida Inventors Hall of Fame and in 2018 into the National Inventors Hall of Fame for her technology contributions to the environmental cleanup field. With 12-issued US Patents, Quinn is a member of the Florida Academy of Science Engineering and Medicine.

Currently, Jackie Quinn is managing the development and delivery of the Polar Resources Ice Mining Experiment-1 (PRIME-1) lunar payload as well as three additional lunar-bound mass spectrometers known as MSolo units. One MSolo unit is manifested on the Volatiles Investigating Polar Exploration Rover (VIPER). PRIME-1, which is comprised of an MSolo unit paired with a meter-long regolith sampling drill, is anticipated to fly to the lunar south pole in late 2024 onboard Intuitive Machine's second lander.

Erica Rodgers

NASA

Dr. Erica Rodgers is the director of advanced programs for NASA's Office of Technology, Policy, and Strategy. Rodgers defines and shapes studies of agency and national importance to provide data- and evidence-driven technology, policy, and strategy advice to NASA leadership. She leads the Science and Technology Partnership Forum and establishes coordination frameworks across U.S. government space agencies. Rodgers provides leadership in developing and advancing strategic policy guidance and identifying emerging technologies and opportunities to inform national space policy and NASA's future mission needs. Rodgers leverages expertise in space science research, spaceflight mission execution, systems engineering, space concepts design, systems and capability analysis of human exploration architectures, and satellite mission operations to lead across OTPS's portfolio.

Phil Root

STO

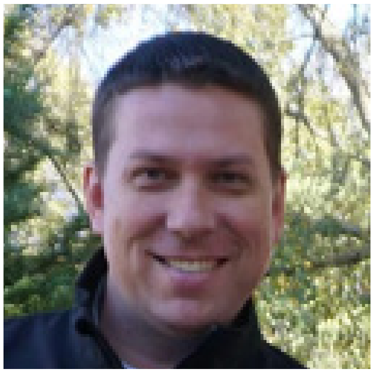
Army Lt. Col. (ret) Philip Root, PhD, was named director of the Strategic Technology Office (STO) in February 2022. He previously served as the Defense Sciences Office's (DSO's) deputy director and acting director from June 2019 until moving to STO. He previously served as program manager within the DARPA's Tactical Technology Office (TTO) where he explored the intersection of AI, autonomy, and military operations. His former TTO programs include the Squad X program, Urban Reconnaissance through Supervised Autonomy (URSA), the ALIAS aircrew autonomy program, the Mobile Force Protection counter-UAS program, the Underminer tactical tunneling program, and the DSO Fast Lightweight Autonomy (FLA) program. He maintains responsibility for the legal, moral, and ethical (LME) analysis of the URSA program as an exemplar for in-depth LME analysis of an autonomous system.

Before coming to DARPA, Root was the director of the Center for Innovation and Engineering at the United States Military Academy at West Point where he oversaw cadet and faculty research in support of Army operations. As a research and development officer, Root has deployed to Afghanistan developing and implementing the hardware and software needed to support cloud-based military intelligence analytics. He served two years as an Astronaut Office support engineer at the Johnson Space Center where he had oversight responsibilities for the booster and launch abort system of the Constellation program intended to return Americans to the Moon. Root spent nearly the first decade of his career as an Apache helicopter pilot in Germany and Korea. He is a graduate of the United States Military Academy, and he received his Master of Science and doctorate from MIT at the Laboratory for Information and Decision Systems (LIDS).

Mehak Sarang

ispace

Mehak Sarang is the Payloads Manager for ispace, US. In this role, Mehak leads payload integration efforts for commercial, NASA, and internal payload customers on the APEX 1.0 Lunar Lander and supports the development of a global strategy for future payloads. She began her involvement with the Commercial Lunar Payload Services program as a payloads integration engineer at Masten Space Systems. Prior to this, she was a research associate at the MIT Space Exploration Initiative and Harvard Business School, studying the role of Public-Private Partnerships in the development of the commercial space industry and developing a shared infrastructure for lunar exploration.



Jason Schuler

NASA

Jason is a mechanical engineer and founding member of Swamp Works – a team at Kennedy Space Center devoted to developing robotic technologies to use space resources. He is a co-inventor of RASSOR - aka Regolith Advanced Surface Systems Operation Robot and has spent the last 16 years developing technologies that will interact with extra-terrestrial regolith. Jason is currently the Principal Investigator for the ISRU Pilot Excavator project to develop a robotic system to demonstrate large scale lunar regolith excavation on the moon.

Harri Vanhala

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.

Spuds Vogel

NASA

Dr. Kurt "Spuds" Vogel is the associate administrator for the Space Technology Mission Directorate (STMD) at NASA Headquarters in Washington, a position he has served since Jan. 16, 2024. In this role, he oversees executive leadership, strategic planning, and management of all technology maturation and demonstration programs executed under the directorate's $1.2 billion budget.

Before leading STMD, Vogel served as director of space architectures within the Office of the Administrator. Arriving at NASA in July 2021, he led multiple space architecture efforts, including the development of the Moon to Mars Strategy and Objectives, forming the agency's blueprint for long-term, human-led scientific discovery in deep space. He also served as chair of NASA's Agency Cross-Directorate Federated Board, whose purpose is to ensure NASA's focus is integrated with common strategic goals and direction across the agency's mission directorates.

Vogel has more than 34 years of U.S. government service, primarily in the Defense Department, as a technical leader, senior program manager, and chief technologist.

Prior to joining NASA, Vogel served six years at the Defense Advanced Research Projects Agency (DARPA), leading innovative research across a portfolio of classified, state-of-the-art, high-risk programs spanning multiple DARPA offices.

From 2008 until 2015, Vogel led research and development at the Air Force Research Lab's Systems Technology Office, where he directed a Defense Department science and technology portfolio. He also served as the acting chief technologist for the National Reconnaissance Office's Survivability Assurance Office.

Vogel retired from active duty in 2010 after serving in the air and space domains during a 21-year career as an officer in the United States Air Force. During his service, he led the USAF Red Team and served as chief technology officer for the Next Generation Bomber program. Vogel also is an Air Force Test Pilot School graduate, having flown over 40 different aircraft as a flight test engineer and civilian pilot.

He holds a Doctor of Philosophy and Master of Science in astronautical engineering from the Air Force Institute of Technology and a bachelor's in astronautical engineering from the United States Air Force Academy. He is a member of the national engineering and aerospace engineering honor societies.

Niki Werkheiser

NASA

Niki Werkheiser serves as the Director for Technology Maturation in the Space Technology Mission Directorate (STMD) at NASA Headquarters, where she leads the advancement of mid-TRL technologies for future space missions. The Technology Maturation portfolio includes more than 100 projects within the Game Changing Development (GCD) Program and the Lunar Surface Innovation Initiative (LSII). These ambitious projects are executed across eight NASA Centers and with dozens of industry and academic partners.

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 which have been demonstrated on the International Space Station (ISS) and directly feed forward to NASA's Exploration missions.

Ms. Werkheiser has over 25 years of experience developing and flying new technologies in space and a proven approach for managing complex projects and programs. She is particularly passionate about creating novel competitive programs and partnerships across the government, industry, and academia. She has received numerous awards, including NASA's Silver Snoopy and Outstanding Leadership Medal, and the American Astronautical Society Space Technology Award.

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.

TECHNOLOGY SHOW & TELL

SPRING MEETING APRIL 23–25, 2024

TECHNOLOGY NAME	AFFILIATION	POC
3D Printed LHP for Deployable Radiators	Advanced Cooling Technologies, Inc.	Bryan Muzyka
Artificial Intelligence/Machine Learning Training	JHU	Bryant Beeler
AstroVinci	Westinghouse Electric Company	Peter Frye
Autonomous Commodity Management	NASA Stennis Space Center	Fernando Figueroa
Cast Molten Regolith Simulant	MIT	Daniel Massimino
Clear Dust Repellent Coating	Zin Technologies / Voyager Space	Robert Fulop
DIABLO	Honeybee Robotics	Vishnu Sanigepalli
Distributed Extreme Environment Drive System	Motiv Space Systems	Tom McCarthy
Dust Tolerant Connector	Honeybee Robotics	Stephen Indyk
Electrodynamic Dust Shields (EDS)	HedgeFog Research	John Bell
Electrostatic and Magnetic Beneficiation	Missouri University of Science and Technology	Daoru Han
FLEX Rover	Astrolab	Marco Valenzuela
Gecko Roller Magnetic Susceptibility Instrument	University of Maryland, College Park	Charles Pett
Haven-1	Vast Space	Tristan Prejean
ISRU Pilot Excavator (IPEx) Polar Resources Ice Mining Experiment-1 (PRIME-1) Cooperative Autonomous Distributed Robotic Exploration (CADRE) Stereo Cameras for Lunar Plume-Surface Studies (SCALPSS)	NASA's Game Changing Development	Marina Guerges
Lunar Equipment Support System & Handling-Placed (LESSH-Placed)	NASA Goddard Space Flight Center	Mark Neuman
Lunar Dust Tolerant Connector	Amphenol Aerospace	Michael Sayles
MAPP Lunar Rover	Lunar Outpost	A.J. Gemer
MOXIE Solid Oxide Electrolyzer	Oxeon Energy	Jessica Elwell
Multi-Scale XR Simulator for Lunar Robotic Activities	Prefixa Inc.	Miguel Arias
Oscillating Heat Pipe	ThermAvant Technologies	Alex Miller
Puli Lunar Water Snooper (PLWS)	Puli Space Technologies	Tibor Pacher
Regolith Immune Linear Actuator Family	Apech Labs	James Diorio
Robotic Leg as Regolith Strength Sensor	University of Southern California	Feifei Qian
Shape-Memory Allow Deployable Radiator Cover	Firefly Aerospace	Joseph Marlin
Space Science Test and Evaluation Facility	Aegis Aerospace	Jessica Piness
Spacecraft Water Analysis with Nanopore (SWAN)	Goeppert LLC	Zehui Xia
Spacefarer: Remote Lunar Operations Software	Mission Control	Kaizad Raimalwala
Soil shear Properties Assessment, Resistance, Thermal, Analysis multiTool (SPARTA)	Jet Propulsion Laboratory	Robert Anderson
TALOS (TALON Altered Lunar Operations System)	QinetiQ US	Matthew Harris
Tech Port	NASA	Nathaniel Booth

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Overview of regolith testing using the SPARTA Toolkit.

R. C. Anderson[1], D. Buczkowski[2], K. Chien[1], M. Duong[1], J. Long-Fox[3], L. Sollitt[4], D.Y. Wyrick[5], and K.Zacny[6], [1]NASA/Jet Propulsion Laboratory/California Institute of Technology, 4800 Oak Grove Dr., Pasadena, CA, 91109, [2]JHU/Applied Physics Laboratory, [3]University of Central Florida, [4]NASA/Ames Research Center, [5]Southwest Research Institute, [6]Honeybee Robotics, (robert.c.anderson@jpl.nasa.gov)

Introduction: In-depth characterization of the subsurface properties of *in situ* planetary regolith is a high priority for future planetary missions. SPARTA is a highly versatile, miniature, multitool instrument that can robotically deploy a cone penetrometer, vane shear, dielectric probe, and thermal conductivity probe into the shallow (<1 m) subsurface of planetary bodies.

The SPARTA toolkit consists of four components (**Fig. 1**): a cone penetration tester (CPT), a vane shear tester (VST), a dielectric spectroscopy probe (DSP), and a thermal conductivity probe (TCP). Physical measurements conducted by SPARTA are soil shear strength, penetration resistance, temperature, thermal conductivity, and the potential presence of water/ice. The CPT and VST test mechanical properties (e.g., shear and bearing strength) by resistance to penetration into the regolith and rotation until failure, respectively. Mechanical properties are deduced from the calibrated voltages (and therefore forces) used to penetrate and break the regolith. The DSP uses an alternating voltage to turn a section of regolith into a circuit; the phase shift and subsequent amplitude of the received current will depend on the chemical properties, including water/ice content. The TCP heats the regolith and measures the changing temperature along the length of the probe as a function of time to determine thermal conductivity, diffusivity, and specific heat. SPARTA provides NASA with a new capability to collect a suite of *in situ* subsurface measurements of the geomechanical, thermal, electrical, and chemical properties of dry or icy regolith.

SPARTA Testing to Date: The goal of SPARTA testing is to demonstrate the operation of the toolkit different components for a variety of planetary environments. Our testing to date has focused on three areas: laboratory, field, and Zero-G environmental (gravity, temperature, pressure).

Laboratory Testing: The early laboratory tests focused primarily on component-level tests under terrestrial environmental conditions. Each component was individually tested using Mars Mojave Simulants (MMS-Mars) and JSC-1a (Lunar) simulants. Recent testing of the SPARTA toolkit have been preformed in Lunar Highlands simulant (LHS-1) and Lunar Maria simulant (LMS-1).

Early Field Testing: The initial field tests of SPARTA were held at Gray Mountain, AZ. Field data was collected for the CPT, TCP, and DSP. No VST data were collected due to software/hardware interface issues.

In 2022, SPARTA was deployed in the GEODES Field Test (SSERVI) at Medicine Lake, CA. This was the first time all four components of SPARTA were tested *in situ* simultaneously.

Recent Field Testing: In February, 2024, SPARTA was deployed to the JPL Mars Yard for testing. The objective was the testing of a new linear actuator and flight software. Two of the components of SPARTA are scheduled for suborbital flight on Blue Origin in June, 2024. This test will focus on the effect of lunar gravity of the VST and the DSP probes. Results from this set of field test will be presented at this meeting.

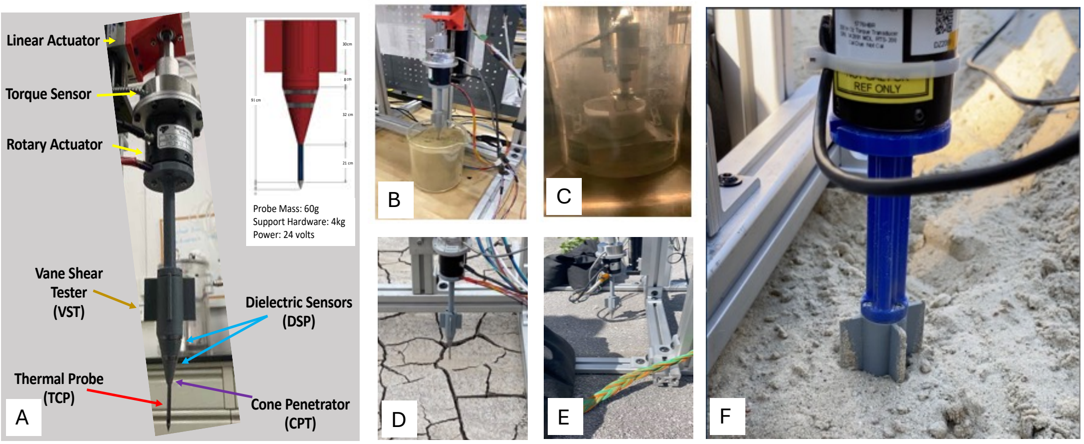

Fig. 1 A) Brassboard showing the major components of SPARTA, B) Laboratory testing in JSC-1a, C) Martian environmental testing in MMS, D) Field testing of SPARTA at Grey Mt., AZ, E) Field testing of SPARTA at Medicine Lake, CA, F) Field testing of SPARTA at the JPL Mars Yard.

Towards a Multi-Scale Extended Reality (XR) Simulator for Lunar robotic activities

Miguel Arias, PhD[1], Bo Varga, MBA[2],
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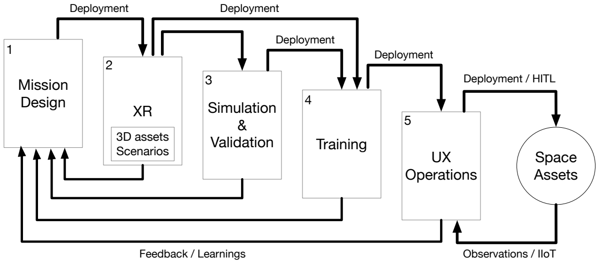
ariasm@prefixa.com

Introduction: 2024 to date four Lunar landers have failed missions as planned. Intuitive Machines, despite (1) failure to turn on laser range finders for landing, (2) failure to achieve planned orbit, (3) crash landed – but on lander side which has no antennas or instruments. The requirement for space missions to reduce mass, volume, power consumption, and cost, while maximizing capabilities, results in complex systems with very limited failure mode resources. To lower risk in ISRU and ISAM Space Missions it is mandatory to maximize extensive tests and validations at all levels of the design and implementation cycle, including monitoring human and robot performance at all levels.

We propose an XR based multi-scale Extended <Reality> Software Platform (ESP) to create and validate mission and process planning, 3D simulations and scenarios, training, mission operations, and human and AI/ML monitoring. The platform is intended for human-in-the-loop (HITL) and, humanoid-robot in the loop (HRITL) operations focuses on physics and physically accurate real time simulation. HRITL looks very likely for mass use in space based on compatibility with HITL operations and systems. Our platform will deliver software to enable regular, reliable, insurable transport to the Lunar surface and construction, excavation, ISRU, and maintenance and support of all assets on the Lunar Surface. The platform builds on previous experience with a NASA JSC training simulator developed by us [1], with added digital twin capability.

Architecture: The main levels of ERSP are (1) mission planning, goals, KPIs, resources, (2) 3D models of assets, environments, plans, outcomes, (3) scenario simulations with real & synthetic data to **enable human & robust testing at all levels**, (4) trainings of HITL and HRITL [2], (5) virtual and real mission operation with asset or environment monitorings via robust IIoT sensors – by HITL and AI/ML with alerts, alarms at all levels – and including robust viewer channels, (6) support from human monitor, remote viewers, and expert systems based on AI/ML monitoring, & (7) future GenAI documentation with human curation and validation.

Work to Date: ERSP has successfully demonstrated (2) based on JSC goals, as well as (3), (4), and (5) baseline performance. Prototype software includes multi-agent (HITL and/or HRITL) redirected walking for training and mission applications, PNT in VR, and spawning multiple scenarios for predictive analytics and synthetic test data for AI/ML development, including alerts and alarms.



The platform enables agile creation and testing of multiple scenarios to map optimum outcomes. IIoT sensor input at any level enables match of actual state versus planned ideal state to enable course correction and predictive analytics.

Work in Progress: Our team delivered vision solutions since 2007 & 3D modeling & simulation solutions today. Port of current Unity software to NVIDIA Omniverse full stack is under way. AI/ML [3] , Digital Twins, and HRITL implementation in ERSP are TRL 3 to TRL 5 tools, CY 2024 goal is TRL 7, with product release CY 2025.

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[3] Nvidia Omniverse Synthetic Data Generation (SDG) to train AI: https://www.nvidia.com/en-us/omniverse/synthetic-data/

Electrodynamic Dust Shields (EDS).

J. Bell, Hedgefog Research Inc., 1891 North Gaffey Street, Suite #224, San Pedro, CA 90731. (Contact: jbell@hedgefogresearch.com)

Introduction: Hedgefog Research has designed, fabricated, and demonstrated EDS devices using high voltage waveforms and simulated regolith to remove dust from surfaces as small as 0.5 in. x 0.5in. to single sheets of 6ft. x 1.5ft in area. The mass is approximately 250 g/m^2 and uses an average power of approximately 0.1mW when operated for 10 seconds each earth day. The EDS technology is based on a combination of customized rigid and bendable plastic sheet forms with thin film electrode arrays fabricated from commercial flexible copper circuit. The two-dimensional flat plastic sheets may incorporate flexible 'living' hinges that can be dynamically bent in either a positive or negative radius to conform to curved surfaces and have been tested over 100,000's of bending cycles without failure. This allows dust to be cleared from thermal radiators, pipes, mechanical actuators and joints, O-ring seals, dust conveyor belts, habitat doorways, and outdoor walkways in high traffic areas on the Lunar or Martian surface.

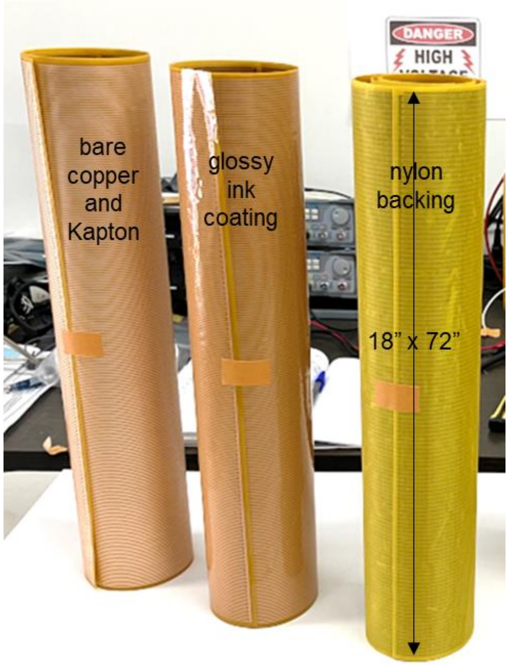


Figure 1: Single piece EDS for flat surfaces, 12μm copper, 25μm Kapton.

Incorporating transparent Indium Tin Oxide as the EDS electrode material allows dust to be cleared from solar panels, displays, viewports, and camera lenses without a significant reduction in optical transparency. Hedgefog Research will fly an EDS experiment aboard the Aegis Aerospace SSTEF-1 mission to the Lunar surface in 2024 via an Intuitive machines lander, with additional testing on the International Space Station as part of the MISSE-22 mission in 2025.

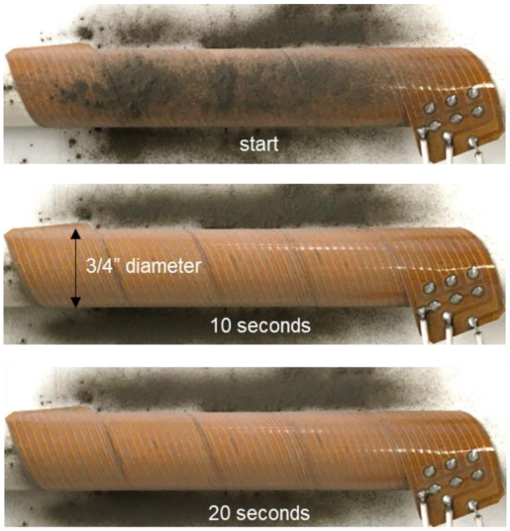


Figure 2: 100μm thick EDS tape wrapped around a pipe, JSC-1A baked dust, <53μm size.

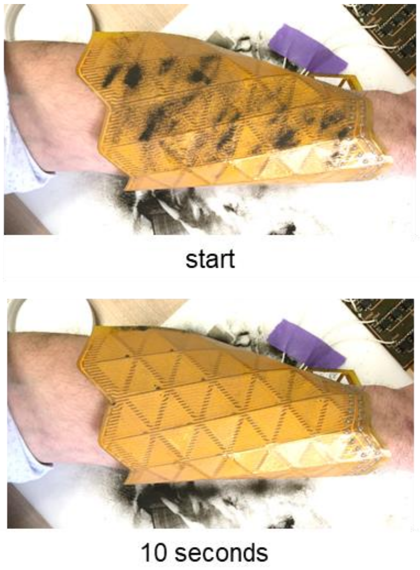


Figure 3: Dynamically bending EDS, JSC-1A unbaked dust, 53-120μm size, @2.6kV, 10Hz, 1mm gap

Acknowledgment: This work undertaken as part of an SBIR Phase I and Phase II with NASA KSC.

OffWorld Prospector: Lunar Oxygen and Hydrogen Production Demonstration. D. G. Bienhoff[1] and O. Borgue, [1]Off-World, Inc., dallas.bienhoff@offworld.ai, [2]OffWorld Europe, olivia.borgue@offworld.ai. (Contact: dallas.bienhoff@offworld.ai)

Introduction: OffWorld is going to the Moon! Our goal is to demonstrate oxygen production from regolith minerals and oxygen and hydrogen production from icy regolith on OffWorld Prospector 1 (OWP-1), the first mission of our OffWorld Prospector Program (OPP). Subsequent missions will incorporate volatiles separation and liquefaction followed by a pilot plant and industrial-scale operations. Multiple participants will provide critical path, parallel path, and non-critical technology demonstrations, plus scientific instruments.

Background: Off-World, Inc., was established in 2016 to develop autonomous mining robots and swarm robotic mining capabilities. To date, we have demonstrated an excavator and a surveyor in operational mines and are about to start production. OffWorld Europe was established in 2022 under an agreement with Luxembourg Space Agency to develop a Lunar Processing Module (LPM). The LPM is to extract water from icy regolith to produce oxygen and hydrogen by 2028. OffWorld US is to provide the mobility unit that will find and excavate icy regolith and procure transportation to the Moon. We called this mission Demo 1.

In November 2023, NASA released its LIFT-1 RFI seeking information on end-to-end demonstration missions to produce oxygen from regolith minerals [1]. The LIFT-1 mission is to be conducted in late 2027. NASA foresees a more capable LIFT-2 mission around 2030 and a pilot plant in 2033.

OP-1 is the combination of NASA's LIFT-1 and OffWorld's Demo 1 objectives.

OffWorld Prospector Program: Industrial scale ISRU that uses every gram excavated is the end goal of our OPP. The first step is OP-1 to produce and story oxygen and hydrogen from regolith minerals and icy regolith. OP-2 will demonstrate increased production rates and liquefy the oxygen and hydrogen. With success, the third mission will establish an ISRU pilot plant producing and storing water, oxygen, and hydrogen.

OffWorld Prospector 1. Our end-to-end OP-1 is scheduled for Q4 2024. The mobility unit, Prospector-1 (Figure 1), will be transported to the lunar south pole region by a commercial provider. Prospector-1 will excavate and deliver regolith to an oxygen-from-regolith processing unit from multiple sites at greater distances from the lander. Oxygen will be captured and stored from each location. Next, Prospector-1 will travel to and enter a permanently shadowed region (PSR) to prospect for icy regolith. Once located, the icy regolith will be excavated and deposited into the LPM. Prospector-1 will leave the PSR to extract and electrolyze water to produce and store oxygen and hydrogen. We repeat this cycle at multiple potential Artemis III landing sites.

OP-1 Participants. OffWorld has contacted 30 potential participants in OP-1. Roles include critical path providers and partners, parallel path providers, and independent technology demonstrations. Critical path roles include transportation, oxygen-from-regolith processing, communications, prospecting, position-navigation-timing, and power generation. Parallel path roles include communications, power generation, water purification, electrolysis, and prospecting. Independent technology demonstrations roles include power transfer and surface communications.

OP-1 Status. OffWorld Europe is testing its LPM breadboard and is heading to PDR in mid-2024. OffWorld US has held the OP-1 SRR and Concept Review and is preparing for a PDR.

OP-1 Schedule. 2024 milestones include submitting a LIFT-1 proposal, conducting a CDR, and signing a transportation contract. Engineering Unit fabrication and procurement, with some assembly, will occur in 2025. Engineering Unit assembly complete and testing happens in early 2026. Protoflight fabrication, procurement and assembly is completed in 2026. Participants' hardware is integrated in Q1 2027. Integration and testing by the transportation provider is scheduled for Q3 2027, with launch in Q4 2027.

References:

[1] NASA STMD Lunar Infrastructure Foundational Technologies-1 (LIFT-1) Demonstration RFI 80HQTR24L002_LIFT1, Amended 12/01/23.

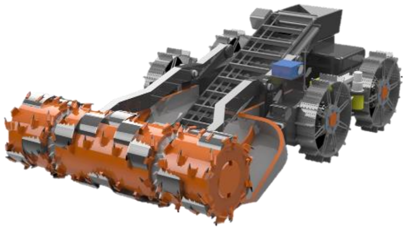


Figure 1. OffWorld's Prospector-1 will produce oxygen from regolith and oxygen and hydrogen from icy regolith.

Decentralized Swarm Autonomy for Site Preparation.

N. U. Bolatto, University of Maryland Space Systems Lab, 382 Technology Dr. College Park, MD 20742. (Contact: nbolatto@umd.edu)

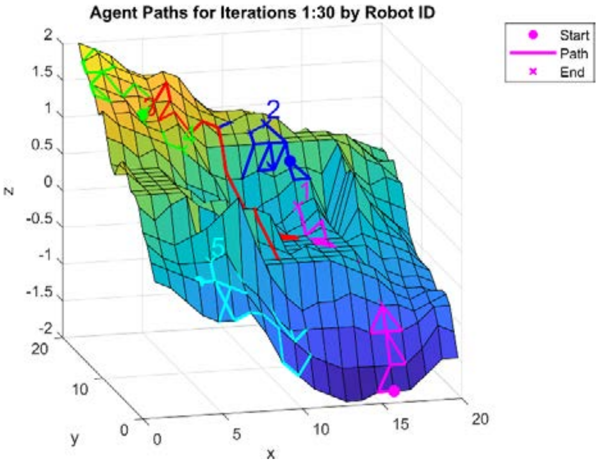
Introduction: Under the Moon-to-Mars objectives, NASA seeks technology that enables lunar infrastructure to scale from the first Artemis landings, up all the way to a continuous human presence and a sustainable supporting economy. The creation of this infrastructure will require large excavation and site preparation projects to do everything from clearing and levelling landing areas, to digging base foundations, to constructing large berms and radiation shields out of bulk regolith. On the Moon or Mars, this must be performed by severely mass-constrained autonomous rovers, meaning that operations of meaningful size are likely to require more than one rover. Medium to large-scale operations such as the clearing and levelling of a surface base or landing pad may require tens of robots acting in concert. A true settlement may require hundreds to construct initial infrastructure, conduct maintenance and expansion, or even assist with ISRU tasks. As such, a scalable, multi-agent modelling approach to future excavation operations will be required.

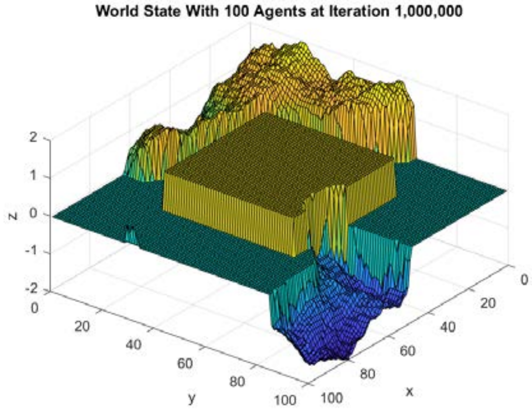
This project seeks to evaluate how robot swarms can address the task of extraterrestrial site preparation and terrain grading. Behavioral simulations like this one can inform future ConOps and mission architectures within the very cooperation-dependent context of off-world site preparation.

Project Overview: The goal of this study is to evaluate the potential of simple behavior rules and emergent behavior in the context of autonomous teamed terrain-shifting. One way to evaluate how a change in algorithm or the number of agents affects task completion is to abstract the initial terrain and goal terrain into 2.5D heightmaps. The two heightmaps can then be differenced to define which areas need material added (negative space) and which need material removed (positive space) to achieve the goal heightmap at any time. Once differenced and regardless of the specific terrain geometry, a single matrix describes how agents should shift terrain at any given time.

Each simulated agent is given a basic ruleset for how they should behave based on their position on the worksite, whether they are carrying material, and what the local geometry is compared to the goal map. Through a decentralized approach, each agent is capable of operating independently of one another. Team progression to a goal does not require central computation, communication, or forward planning. Because of this, the team of simulated rovers still operates without significant overhead even when team size multiplies from just several individuals to over several hundred agents.

This work demonstrates a new application of decentralized swarm behaviors for site preparation tasks in a highly customizable virtual environment. The framework is shown to be capable of full swarm simulations, allowing for a magnitude increase in agents or map size (figures below). Two different Cocktail Party-style decentralized behaviors are demonstrated, a random-walking “Blind” behavior and a more directed “Guided” behavior. While the Blind behavior is very simple and computationally cheap, significantly better task completion times were found using Guided behavior. Most importantly, both methods of decentralized control are shown to allow 100+ agent teams to successfully complete a terrain-shifting task.





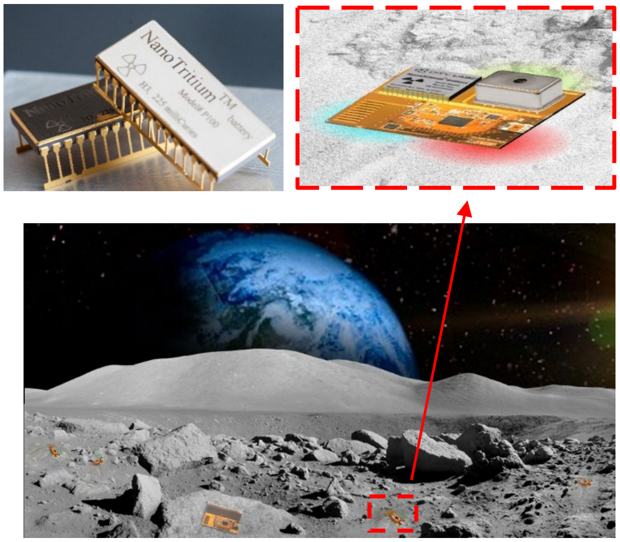
(terrain height differences are exaggerated)

Tritium Micropowered Sensors for Extreme Environments. P. Cabauy[1], J. P. Grant[1], and M. A. Stone[1], [1]City Labs, Inc., 12217 SW 131st Ave, Miami, FL 33186. (Contact: peter.cabauy@citylabs.net)

Introduction: Conducting on-site analyses in the Moon's south pole region poses a formidable technical obstacle. The extreme cold of the dark, cratered areas in the Moon's south pole, where temperatures plummet to as low as -248 ºC, creates a hostile environment with minimal solar power availability. This limitation hampers traditional battery-powered equipment, thus constraining scientific opportunities. Our proposed solution introduces a novel approach to powering sensors in such harsh conditions: betavoltaic batteries. These batteries generate electric power from radioactive decay, offering distinct advantages for lunar surface operations. They can function at significantly lower temperatures and withstand a broader range of environmental conditions, including extreme vibration and altitude, compared to conventional batteries. Tritium betavoltaics, in particular, have a proven track record of delivering consistent nanowatt power under extreme environmental conditions, thanks to tritium's half-life of 12.3 years and its solid-state formation, which renders it resilient to temperature extremes. For instance, City Labs' P100 NanoTritium™ betavoltaic, a generally licensed tritium betavoltaic, has been qualified to provide continuous power for over 20 years across temperatures ranging from -55 °C to 150 °C [1,2].

To address NASA's scientific and human exploration goals in cold environments like the moon, we propose the development of nuclear-micropowered probes (NMPs) driven by microwatt-level tritium betavoltaic sources, heralding a new era in this field. Although beta fluxes yield lower power generation rates than solar photons, typically in the nano- and micro-watt per square centimeter range, tritium's lengthy half-life ensures that the sensor system can operate for more than two decades. The technological innovation of tritium betavoltaics in NMPs offers a groundbreaking bridge between these lunar resources—water and power—making feasible lunar science measurements in these extremely harsh and frigid environments and subsequent utilization of these resources. The impact would be a resilient, cost-effective, and energy-efficient technology that enables the acquisition of previously unattainable measurements to characterize the abundance and location of lunar volatiles, such as water, in support of a permanent human presence.

Applications for this tritium-powered sensor system in space are extensive. It seamlessly integrates into satellites, enhancing sensing capabilities in dimly lit or shadowed regions. One innovative application involves a self-powered imaging sensor integrated into spacecraft and satellites as an autonomous node, obviating the need for wire conduits or structural modifications. Another application is the Low Power Frequency Beacon, a technology that significantly enhances space situational awareness, addressing critical mission requirements. Tritium betavoltaics are an enabling technology that holds substantial promise for enhancing our understanding of the geology and resource characteristics of the mysterious dark lunar craters and the Moon as a whole by enabling the exploration of previously inaccessible regions to ground-based study due to technological limitations.



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[2] D. S. Cheu, T. E. Adams, and S. T. Revankar, “Experiments and modeling on effects of temperature on electrical performance of a betavoltaic,” Nucl. Eng. Des., vol. 325, pp. 256–260, Dec. 2017, doi: 10.1016/j.nucengdes.2017.06.028.

Technology Readiness Assessment Framework for Fuel Cell and Electrolyzer Systems. K. P. Cain[1], P. J. Smith[1], R. P. Gilligan[1], and I. J. Jakupca[1], [1]NASA John H. Glenn Research Center, 21000 Brookpark Road, Cleveland, OH 44135. (Contact: kerrigan.p.cain@nasa.gov)

As electrolyzer (EZ), primary fuel cell (PFC), and regenerative fuel cell (RFC) technologies advance for space applications, technology readiness assessments are imperative for identifying and characterizing the challenges for systems to become flight-ready. There needs to be a consistent method to compare technology readiness levels (TRLs) and advancement degree of difficulty (AD^2) for these systems and invested stakeholders given the various concepts of operation, electrolyte chemistries (e.g., alkaline, proton exchange membrane, solid oxide, etc.), and system designs that are in development to fill the gaps required by these applications, [1], [2]. A standardized process applicable to developmental EZ, PFC, and RFC systems is presented that provides a common foundation to accurately compare systems across the technology landscape.

The first step in this process is defining the mission use case, or target application, for the evaluated system. For PFC systems, use cases could be providing power on a spacecraft, rover, or other mission that requires power. The use case for EZ systems could be cabin oxygen generation, high-pressure oxygen generation, or propellant generation from lunar or Martian water. For RFC systems, use cases could be energy storage solutions for habitats, rovers, or spacecraft.

The second step for all use cases is accurately defining the operational and non-operational environments (OE and NOE respectively), which then define relevant environments (REs). The OE is the environment in which the system will be operated. The NOE is the environment the system is exposed to and expected to survive while not operational. For example, for a PFC system integrated on the exterior of a lunar rover, the OE is all of the expected conditions on the lunar surface during the mission (e.g., temperature, pressure, radiation, dust, 1/6th gravity, etc.) and the NOE includes all of the expected conditions during transit to the lunar surface before operation (e.g., shock and vibration during launch and landing). The RE is then a representative subset of the OE and NOE that is required to demonstrate system performance to mature the technology for the identified mission. Components, subsystems, and systems that have already demonstrated performance in OE and NOE environments may be excluded from further subjection to these environments during technology maturation, except in instances of novel use or configuration. Furthermore, it is possible that certain systems that have multiple use cases can have REs that are bounding, indicating that systems can become flight-ready for more than one use case by demonstrating performance at more stringent conditions.

An underappreciated aspect of this process is the system architecture, with the internal and external interfaces defining where a technology or system resides in reference to the overall mission architecture. This consists of all interfaces through which energy, mass, or force move among and between various levels of the system and mission hardware. For a PFC system, there are multiple subsystems and components that comprise the system (e.g., fuel cell stack, fluid and thermal management, power management and distribution, avionics, etc.) and a portion of these subsystems and components are crucial to the system technically maturing.

Once the key elements are identified, a TRL and AD^2 evaluation must be completed for each key component, interface, subsystem, and system with documentation of justifications for each evaluation. It is important to note that within the defined architecture, the element with the lowest TRL and highest AD^2 will constrain the TRL and AD^2 of the entire architecture. For example, for a PFC system where the fuel cell stack is at a TRL of 4 and AD^2 of 7, but all other subsystems and components are at a TRL of 6 and AD^2 of 5, the PFC system is at a TRL of 4 and AD^2 of 7 until the fuel cell stack matures further and reduces technical risk.

The process outlined here can and should be utilized not only for TRL, but also manufacturing, software, and modeling RLs (MRL, SRL, and MoRL respectively). Once completed, this process provides a foundation to evaluate EZ, PFC, and RFC systems in a common framework.

References: [1] Hirshorn S. and Jefferies S. (2016) Final Report of the *NASA Technology Readiness Assessment (TRA) Study Team*. [2] Kimmel W. M. et al. (2020) *Technology Readiness Assessment Best Practices Guide*.

Maturing Aluminum Extraction from Lunar Regolith: Current Status of the LuSTR MAGMA Project.

K. M. Cannon[1], A. Ignatiev[2], G. L. Brennecka[1], C. Brice[1], C. B. Dreyer[1], J. Kim[1], Z. Yu[1] and the MAGMA team, [1]Colorado School of Mines, 1500 Illinois St., Golden, CO 80401, [2]Lunar Resources Inc., 6721 Portwest Dr., Houston, TX 77024. (Contact: cannon@mines.edu)

Introduction: Previous work on high-temperature regolith processing focused on oxygen as the main product or looked at iron and titanium that would be extracted from mare regolith at equatorial landing sites. With the current goal of building up infrastructure at the lunar south pole in highlands terrains, aluminum is a much more viable metal and has diverse applications in power transmission, radiators, and structures like towers. The MAGMA project (Molten Aluminum Generation for Manufacturing Additively) is a LuSTR23 selection to mature technology for extracting aluminum from regolith at the lunar south pole and turning it into an additive manufacturing feedstock. Here, we provide an update on the current project status and future plans.

MAGMA Overview: MAGMA is being led by Colorado School of Mines with Lunar Resources as the sole industry partner. The team has expertise in lunar geology, ISRU hardware, metallurgy, materials science, and additive manufacturing. The main technology being pursued is Molten Regolith Electrolysis (MRE), which operates directly on raw regolith of any composition without the need for an electrolyte or other consumables shipped from Earth. The overall goal of the project is to work toward an integrated test in vacuum that produces pure aluminum from highlands regolith simulant and casts it into a wire that would be appropriate for additive manufacturing applications. The work is broken up into sub-tasks as described below.

MRE Reactor and Wire Casting: Lunar Resources is providing the MRE reactor based on past work that has demonstrated aluminum production at the benchtop scale. An approximately one-meter diameter system will be used and throughout the project we will switch from operating in air to operating in vacuum as part of the TRL maturation.

Additionally, Lunar Resources is developing a new casting system as part of this project to transform the molten aluminum tapped out of the reactor into a wire feedstock. The casting system is currently in the early design phase.

Tap/Launder System: Multiple taps and launders are needed to move molten products to different parts of the system and ultimately to expel final products (metals) and residual slag from the reactor. So far, we have done preliminary work to understand the viscosity and flow conditions of the metals and slags, which will feed into the tap/launder design options. We are also canvassing taps used in foundries. The next steps are to carry out a system requirements review for the taps/launders and move forward with multiple design options that will be prototyped and tested with room-temperature fluids of representative viscosity.

Materials Compatibility: The tap/launder hardware will come into contact with high-temperature (1600–2000 °C) liquids including metals and oxide slags. This presents a materials compatibility challenge including withstanding high temperatures, keeping strength at those temperatures, limiting corrosion, and limiting wettability. We have identified a set of candidate materials including alumina, graphite, silicon carbide, boron nitride, zirconia, and SiAlONs. Current lab experiments are measuring wetting angles and corrosion of these candidates with synthetic versions of the molten regolith and metal/slag products.

Computational Thermodynamic Modeling: The phase equilibria at different steps of the MRE process will determine which products form, how they will behave in the reactor, and the expected purity of the final metal products. We are using FactSage to model the thermodynamics of the system and have started by tracing out the compositions of the two regolith simulants we plan to use in the project as they are chemically reduced. Later work will explore a broader range of compositions from lunar data that represent likely southern polar regolith.

Aluminum Wire Evaluation: The project will result in cast aluminum wire intended for additive manufacturing. The properties and quality of the wire are important to characterize and potentially improve by modifying the MRE process. We intend to measure grain structure, defect size, chemical composition, and draw-ability of the wire product. Early work will carry out these measurements on off the shelf aluminum wire to serve as a baseline; when wire is available from the casting process we will characterize it with the same techniques, and ultimately will do the same for the end-to-end demo working from regolith simulant to wire.

Reliability Modeling and Analysis of DC Space Microgrids.

Leila Chebbo and Ali Bazzi, University of Connecticut, Storrs, USA, (Contact: Leila.chebbo@uconn.edu)

Introduction: Long-term human presence in space requires a reliable power system (microgrid) that can operate autonomously in a self-sufficient manner [1]. Given the extreme environmental conditions in space, the criticality of some electrical loads, and other logistic requirements, syudying reliability of space microgrids is crucial. Reliability modeling provides a broad knowledge of the potential failure modes of the subsystems and the importance levels of their components. In addition, it helps harden the system design. Consequently, this paper presents a reliability model based on fault tree analysis (FTA) of space microgrids.

DC space microgrid architecture: This study considers the DC space microgrid proposed in [2]. The main components of the studied distribution system are 1) three boost converters (C1, C2, and C3) that convert the different generated voltage levels to a 270V bus, 2) a DC generation bus (GB) that connects all generators and energy storage to different loads, and 3) three buck converters (C4, C5, and C6) that convert the 270 V distribution voltage to the 125V load voltage.

Reliability modeling and assessment: The primary and first step in developing a fault tree to evaluate the overall system reliability is classifying the criticality of the load and defining the “reliability objective.” Since astronauts’ life support is a significant concern in deep space habitats and is directly tied to the power system availability, the primary reliability objective in the microgrid of a crewed system is to support the 16 kW critical loads. However, to maintain the operation of the habitat and automatically detect the failures in an un-crewed system, supplying the 7kW monitoring and communication loads is the primary objective. Other loads in a small six-person habitat are ranked by criticality in Table I [3].

To develop the fault trees of the system, more than 150 scenarios representing the various operational conditions are simulated using a modular space habitat model [4]. Figure 1 shows the developed fault tree of a crewed system during day hours. The fault tree describes the root causes of the top event, which represents the failure of the electrical system to achieve its primary objective. Using the structure importance coefficient in (1) and the developed fault tree, a qualitative reliability assessment of the system components is achieved. Figure 2 shows the components importance coefficient in crewed system during day and night hours.

$$I(i) = 1 - \prod_{X_i \in K_j} \left(1 - \frac{1}{2^{N_j-1}}\right) \tag{1}$$

Table I: Generation units and loads characteristics in crewed and un-crewed systems.

Power generation and loads	Power (kW)	Criticality in crewed	Criticality in un-crewed
Nuclear generator	29	For nominal demand	For nominal demand
Solar Generator	28.4	For peak hours	For critical situations
Life support loads	16	1st priority	3rd priority
Monitoring loads	7	2nd priority	1st priority
Other loads	6	3rd priority	2nd priority

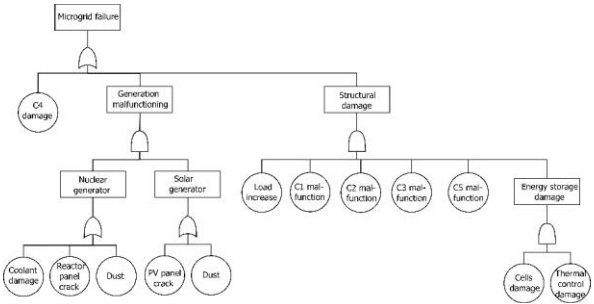

Figure 1: Fault tree diagram in a crewed system during day hours

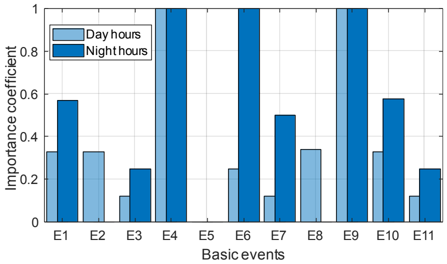

Figure 2: Components importance coefficient variation.

Conclusion: In conclusion and based on the calculated importance coefficient, the most critical components in a crewed system are the GB and C4. Therefore, to improve the system reliability, it is required to reduce the dependability on these components through a redundant power system architecture and power rerouting strategies.

References: [1] M. S. Anderson et al., “Life support baseline values and assumptions document,” techreport, 2018. [2] L. Chebbo, et al. "Modeling and Operation of Microgrids for Deep Space Habitats Under Environmental Disturbances." 2023 IEEE PECI. [3] H. Jones, “Power Management for Space Advanced Life Support ” Power, 2002. [4] Mohsen Azimi, et al. "HabSim: A Modular Coupled Virtual Testbed for Simulating ExtraTerrestrial Habitat Systems," AIAA Journal, 2024.

GEGSLA: Global Expert Group on Sustainable Lunar Activities.

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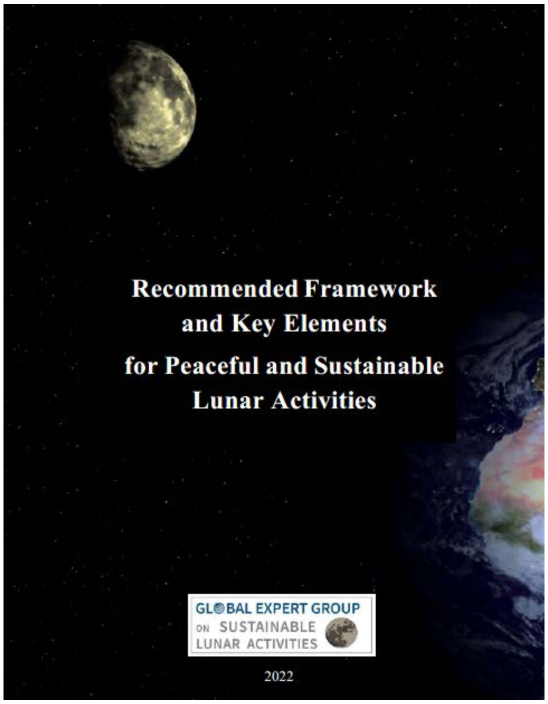
Introduction: This presentation will summarize the outcomes, status, and future activities of the Global Expert Group on Sustainable Lunar Activities (GEGSLA) proposed and hosted by the Moon Village Association (MVA). [1] In February 2021, the Moon Village created a multistakeholder forum for the discussion of critical issues for lunar coordination. GEGSLA carried out its first phase of work until December 2022 and came to the adoption of the “Recommended Framework and Key Elements for Peaceful and Sustainable Lunar Activities”, which was published at the MVA website and presented to the 60th Session of the UNCOPUOS Scientific and Technical Subcommittee. [2]



Recommended Framework
and Key Elements
for Peaceful and Sustainable
Lunar Activities

GLOBAL EXPERT GROUP
ON SUSTAINABLE
LUNAR ACTIVITIES

2022

Framework Document: This Framework Document is considered a starting point to initiate a conversation on lunar coordination, and it was agreed upon by consensus by GEGSLA members. The members acted in their individual capacities, but are also stakeholders in lunar activities, including representatives from space agency/government, industry, international organisation, academia and civil society.

The Framework Document comprises two parts: “Principles” and “Key Elements for Sustainable Lunar Activities”, which includes chapters on Information Sharing, Safe Operations and Lunar Environmental Protection, Interoperability, Lunar Governance, Benefits for Humanity, Sustained Lunar Economy, and Human Interaction.

Operational Phase: In 2023, GEGSLA started a new operational phase with the goal of promoting verification and implementation of the Framework Document as well as exchanging information on ongoing and planned lunar missions. This presentation has the goal of promoting GEGSLA outcome documents and encouraging participation in its activities to support its mission of creating a common level playing field for coordinated, sustainable, and peaceful lunar activities. Three working groups were established for the operational phase: 1) Lunar Environmental Protection, 2) Lunar Technical Coordination, 3) Lunar Multistakeholder Coordination.

The objectives of the Lunar Technical Coordination working group align well with the objectives of LSIC. Those objectives are 1) facilitate information sharing between organizations performing missions on the lunar surface, or planning lunar surface missions 2) communicate GEGSLA Recommended Framework to lunar stakeholder community and receive feedback 3) determine the highest priorities for the definition and agreement of best practices to ensure efficient and safe lunar activities, while protecting the lunar environment 4) work toward those best practices being implemented by organizations operating on the lunar surface 5) coordinate technical standards to further the goal of compatibility and interoperability.

Conclusion: Activities on the lunar surface are inherently international in scope. Coordination and the establishment of best practices and interoperability are goals of many organizations. LSIC and GEGSLA, particularly the Lunar Technical Coordination working group, are uniquely suited to work together to bring about shared goals.

References: [1] G. Reibaldi, et al. (2023) IAC-23-D4.2.4 [2] GEGSLA, *Recommended Framework and Key Elements for Peaceful and Sustainable Lunar Activities,* https://moonvillageassociation.org/gegsla/documents/gegsla-recommended-framework/

Lunar Proving Ground: On the Earth or the Moon?

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Introduction: This presentation examines the question of which Lunar Proving Ground facilities should be on the Earth and which need to be located on the Moon. The main determinant concerns the availability of real lunar regolith and real lunar dust. One crossover question concerns whether it would be beneficial and feasible to return a large quantity of regolith and dust from the Moon for use in earth-based facilities. Alternatively, it might be possible to install an LPG on the Moon.

Regolith Simulant for Earth-based Facilities: Regolith Simulant is suitable for many types of test in an Earth-Based facility, notably in a "dirty/dusty" thermal-vacuum chamber. FIGURE 1 shows the custom-built thermos-vac at Michigan Technological University that uses regolith simulant. The lunar simulants currently available on Earth are good for certain types of testing such as geotechnical, abrasiveness, and construction. However, certain characteristics of actual lunar regolith are poorly simulated such as the presence of agglutinates or the nanophase iron inclusions in real lunar regolith and the impact glass shards

FIGURE 1. Existing Dusty Thermal Vacuum Chamber at Michigan Technological University's Planetary Surface Technology Development Lab. Credit: Paul Van Susante.

Real Lunar Regolith and Dust for Earth-based Facilities: Real lunar regolith and dust are necessary for electrostatic and charged particle studies, which would require importing large quantities in the hundreds or thousands of kilograms from the Moon. The need for authentic lunar material raises the trade question of the cost of a lunar return mission versus the cost of locating a facility on the Moon.

Real Lunar Regolith and Dust on the Moon: Emplacing a LPG facility on the Moon would solve the problem of obtaining real regolith and dust. However, it introduces the challenge of building, launching and landing an LPG module on the Moon and staffing it. Operations of the thermos-vac would share much in common with the Earth-based version except for creating a vacuum

References:

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System Engineering & Integration (SE&I) In-Situ Resource Utilization (ISRU) Modeling and Analysis (SIMA) Tool for Subsystem Integration into full-scale Architectures.

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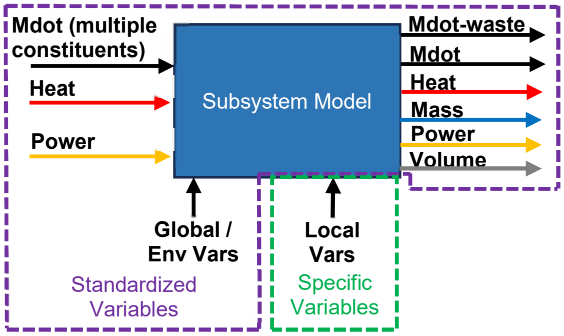
Introduction: In situ resource utilization (ISRU) is the practice of producing mission consumables from local lunar/planetary resources, thereby minimizing system launch mass requirements, mainly through the production of propellant fuel components and life support resources. Modeling full ISRU technology architectures significantly impacts the design and optimization of individual unit processes and facilitates their introduction into service with the Science Technology Mission Directorate (STMD) logistical planning and operation space [1]. The Mission Analysis and Integration Tool (MAIT) is a modeling framework that connects individual ISRU subsystem models for the purposes of technology downselect, scaling & optimization, and end-to-end process planning. The development project team seeks to address specific STMD capability gaps by simulating ISRU systems in MAIT. The goal is to produce system architectures for the Moon and Mars that are linked to Key Performance Parameters (KPP) and environmental requirements. To that end, the framework is adaptive, flexible, and suitable for collaboration among government, private sector, and international entities. Our approach currently provides conventional outputs, such as mass, power, and volume, to analyze whole system trade spaces. However, the framework was designed to validate current breadboard subsystems, simulate future process design capacity, and allow flexibility to any external developer-driven subsystem model that is in a state of evolution.

Model Details: MAIT consists of modular elements that read and pass information between individual subsystems (see figure right) forming a larger system process. The modules are able to access files written in multiple software languages, and the “drag-and-drop” data manipulation allows for customizable process flow diagrams according to the desired end user need. The MAIT framework consists of three parts: a user-defined master list of subsystem variables, the process flow environment encoded in Simulink (Mathworks graphical programming suite) [2], and the subsystem model files prepared by technology developers. The modules in the process flow environment contain code that interacts with the subsystem software, pass important information to the model, and ultimately run the model and record the results.



Example Use Case: A lunar water mining architecture is one system process design being considered for the production of propellant [3], where water vapor is sublimated from icy Lunar regolith, and electrolyzed to produce oxygen. MAIT connected all subsystems in the product development path, and coordinated developer models ranging from regolith excavation, particle size sorting, heat transfer and sublimation of water vapor, and finally electrolysis, liquification, and storage. Several production targets were investigated including a 1, 10, & 50 metric ton architecture. At the time of this abstract, the parametric runs are still in process and the data is being analyzed. The results will show optimal mass, power, and volume correlated to the dimensions (screw diameter and length) and heater setpoint in the Lunar auger dryer (LADI) subsystem. Another parametric study on the same system model includes trading the Solid Oxide Electrolysis (SOE) versus Proton Exchange Membrane (PEM) downstream subsystems. Preliminary results indicate that further decreases in power demand could be realized with modifications to proton conduction in the electrolysis unit.

Future Work: In addition to improving MAIT’s core processing ability, numerous ISRU architectures are expected to be developed. In the short term, there are plans to investigate Molten Regolith Extraction (MRE) technologies and Mars propellent production.

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Evaluation of Structural Health Monitoring Capabilities in Epoxy-MWCNT Composites Exposed to High Doses of UV Radiation.

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Introduction: NASA seeks to identify and develop materials which will decrease launch mass and increase functionality, maintainability and safety of Lunar structures. Multi-functional materials, especially those incorporating ISRU, have the potential to fulfill these requirements through methods such as structural health monitoring (SHM) [1]. Inclusion of multi-walled carbon nanotubes (MWCNTs) in a polymer matrix leads to formation of internal nanotube networks, which enable real-time in-situ SHM via tracking of changes in electrical properties and correlation with material behavior [2,3]. Intense UV radiation such as that experienced on the Lunar surface instigates the formation of similar entangled networks of MWCNTs on the material exterior [4]. This research explores the effects UV exposure and creation of these networks on the capacity for SHM in Epoxy-1% MWCNT samples subjected to monotonic compressive loadings. These tests confirm the viability of this material as a multifunctional binder when subjected to similar environmental stressors, and paves the way for its utilization in the creation of high mass-loading Lunar regolith composites incorporating SHM properties.

Method: Samples consist of Epon 862 Epoxy resin and Epikure Curing Agent W in a 100/26.4 ratio by weight, with the addition of 1% MWCNT by weight to this mixture. Cylindrical ASTM D695 samples were created of this material. The experimental group was exposed to ~500 MJ dosage of UV radiation in the 290-400 nm range (comparable to ~52 days of continuous solar exposure on the Lunar surface [5]) using a custom exposure chamber. Both control and experimental groups were tested in an Instron uniaxial testing frame at a crosshead displacement rate of 1.3 mm/min while an LCR meter passed 10kHz, 2V AC through attached electrodes. Resistance, reactance, force, and displacement values were monitored and recorded in real-time throughout each test.

Results: Both sample sets showed significant SHM capabilities, though differences in mechanical and electrical behavior were noted between control and UV exposed groups. Resistance and reactance gauge factors [3] calculated and correlated with stress/strain curves show strain sensing (decreasing $\Delta R/R_0$), instances of damage (failure spikes) and continuous damage propagation (exponential increase in $\Delta R/R_0$) as shown in Fig 1.

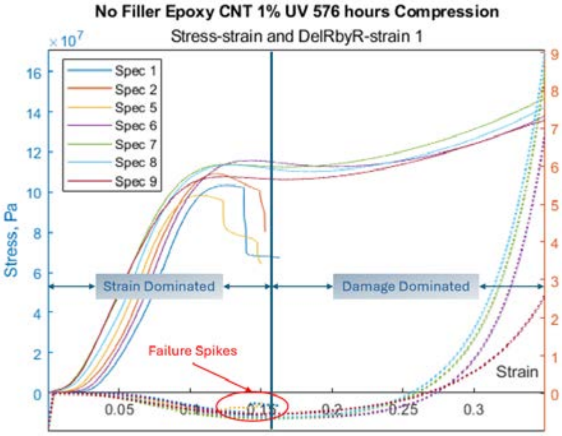

Fig. 1: Strain/damage sensing in resistance regime, UV exposed sample set.

Conclusions: Intense, long-term UV exposure appears to affect mechanical properties and failure characteristics of epoxy-1% CNT samples. However, strain and damage sensing capabilities persist. This bodes well for use of the CNT-doped polymer as a binder for upcoming tests of high-mass loading regolith simulant-polymer-MWCNT composites, as SHM will similarly remain viable after protracted exposure to UV radiation.

Infusion Path: Possible infusion paths include application of this material as a binder in regolith composites in habitat, landing pad, and other infrastructure projects, especially in Lunar polar regions where intense continuous exposure to UV radiation will be significant.

Future Work: Subsequent experimentation will focus on incorporation of epoxy-CNT binder into 80% regolith simulant (by weight) composites. Binder and CNT content will be varied until acceptable levels of SHM are achieved, and these samples will then be exposed to UV to confirm that sensing capabilities persist.

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Reevaluating Mining & Mineral Processing Technology Needs for Lunar ISRU

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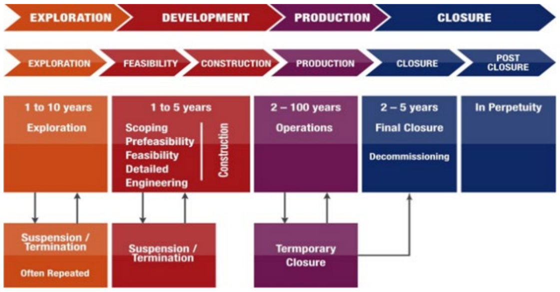
This paper revisits the mining technology needs for Lunar ISRU, based on insights and lessons learned from terrestrial mining. This reevaluation has significant implications for both feasibility and scalability of lunar mining activities.

At the macro level, terrestrial mining has developed a systematic, unified, methodology for discovering mineral resources, evaluating the economic and technical feasibility of extracting those resources, extracting ore from the economic resource, and then processing the ore to extract the metal or mineral of value – as illustrated in the figure below.

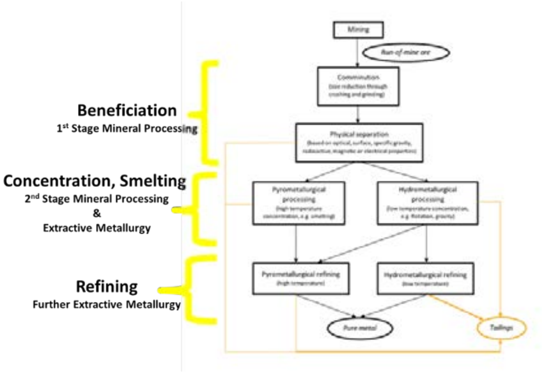


The Stages of Terrestrial Mining [1]

Based on the above, and a scan of prior and current research on lunar mining, it is apparent that significant technology development is required with respect to the Exploration, Feasibility and Construction stages of lunar mining.

For the Production stage, and in particular "Primary Production" (fragmentation, excavation and haulage) the current state-of-the-art for mobile lunar mining machines builds upon design paradigms borrowed from proven, highly successful, lunar rovers – i.e. designs which are appropriate for non-repairable high-reliability systems with finite mission lives (i.e. long MTBF, no MTTR). In contrast, the development of a viable lunar ecosystem will require a shift to a completely different set of design and operating paradigms for the mobile equipment required for mining lunar resources: very long-lived, repairable systems that achieve high mechanical availability – i.e. systems where the ratio of MTBF to (MTBF+MTTR) is high. This will need to be enabled by applying "Design for Repairability" and "Design for Maintainability" concepts to the development of these future machines, assisted by embedded IOT-driven diagnostics and prognostics, and both diagnostic and predictive maintenance decision making based on IOT data.

The remainder of the Production stage consists of further treatment of the mined ore through mineral processing and extractive metallurgy, as illustrated in the figure below.



Mineral Processing & Extractive Metallurgy – adapted from [2]

Given that the mineralogy and geometallurgy of lunar regolith is so dissimilar to terrestrial ore bodies, this area also requires significant focused technology development, ideally based on lunar ore samples.

This paper reviews these diverse technology gaps, and proposes a road map to address them.

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Digitally Engineering a Lunar Mission Ground Station

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Introduction: There have been many outposts proposed for the lunar surface starting with the 1958 Lunex Project to the 2017 Artemis Program currently being pursued. Most of these pursuits were document-driven efforts that were data limited and slow in evolving into a concept. With today's technology system engineers can utilize Digital Engineering tool suites to ingest massive amounts of data collected over the preceding decades delivering data-driven solutions to design the Infrastructure, Logistics, Operations, Maintenance, and Sustainment (ILOMAS) required for the realization of the Lunar Mission Ground Station. As part of this process, the Enterprise requires an understanding of the current technology available and its limitations, construction methods, lunar topography, and the austere environment that will challenge this endeavor.

Providing the Vision: NASA has led the way with setting out the Moon to Mars Objectives, Strategy, and Architecture Definition Document (ADD). The ADD, ~60 years in the making, provides the space architecture encouraging industry to engage the process of defining/refining the functions in their selected swim lane. Digital Engineering will allow industry's system models to plug into the 'federated' Space Architecture model furthering science and space exploration.

Ingesting the Past to Enable the Future: While the ADD is a living document that changes over time as requirements become more focused and as increased knowledge/technology becomes known, focus on is required to facilitate success. This is where Systems Engineers utilizing Digital Engineering assets can begin to develop a Digital Model of NASA's desired architecture while allowing developers to design their systems to plug and play into that architecture. The first crown jewel of that architecture is the establishment of a permanent presence on the Lunar surface, and DE, specifically Building Information Management for Infrastructure (BIMi), is the force multiplier that can make that possible.

Building Information Management for Infrastructure (BIMi): BIM for Infrastructure requires thinking of **B**uilding as a verb as you are "building" the entire LMGS system to include communications, utility routing, facility location, roads, waste management, ISRU, refueling stations, power production and topography. All the data ingested informs the development of the LMGS Digital Model and is shared across the Enterprise by the design team with all the stakeholders facilitating collaboration and information sharing. Stakeholder Engineers collaborate and add discipline-specific data to a 'federated' model.'[1] BIMi facilitates the demonstration of an increased level of design and understanding. BIMi will inform the development of the Digital Model (DM) that will ultimately become the Digital Twin (DT) of the Lunar Mission Ground Station.

- Providing data-driven solutions for ILOMAS required for a Lunar Mission Ground Station located in an austere environment
- Facilitating forward planning by construction crews where they can investigate and perfect construction techniques and methods while interfacing with the design team
- Increasing understanding utilizing Virtual Reality, allowing stakeholders to experience the LMGS as if they were standing on the lunar surface viewing the infrastructure either from the inside or outside the facility during design, construction, and operations phases
- Allowing for refining techniques/methods for construction, testing, and project/asset management
- Enabling visualization of all models in a single environment, fostering coordination and development of designs, enhancing clash avoidance and detection, and improves time and cost decision-making
- Mitigating uncertainty for developers when designing their systems by defining interoperability standards and guiding commonality of systems such as prime mover design
- Utilizing Digital Terrain Elevation Data (DTED) to allow for phased expansion and positioning structures in proximity to the resources being utilized.

References: [1] *McPartland, Richard (11 September 2017). "What is a federated Building Information Model?".*

Characteristics of an Artemis Lunar Construction Modular Toolkit.

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Introduction: Modularity and complementarity are of high value for lunar construction, especially to the early stages of lunar base development. By leveraging the combined capability of many early construction systems, these attributes enable flexibility to meet a wide range of early construction needs in different locations, scalability, maintainability in a harsh environment, and reusability in different locations for economical re-use of down-mass for lunar development. System strengths of each element augments the capabilities of others.

Understanding that lunar construction of early and sustained infrastructure will rely on a variety of construction elements and techniques, we will examine the possible modular and complementary elements of a lunar "toolkit". This is meant to serve as a roadmap to include larger elements of increased complexity, and provides a method for evaluation of different technologies and their deployment. This work will consider the complementarity of the following three elements:

- The NASA AMES ARMADAS construction system [1] - A cuboctahedron truss based general assembly system that can be flat packed for cis-lunar transit, and then robotically assembled and reconfigured into a large variety of configurations.
- The NASA KSC IPEx excavator [2] - A low mass robotic lunar regolith excavator system that can dig, haul, and deposit 10 metric tons of regolith per lunar day.
- The University of Arizona/JPL/MDA LUNAR-BRIC construction system [3] - A reusable regolith filled bag system that can be used for radiation shielding or rocket blast protection.

Module Categorization: The elements are broadly categorized as:

Construction Units being the Toolkit modules that are consumable structural elements. They include the ARMADAS truss voxel (at left) and LUNAR-BRIC Regolith Containment Units (below, right).

Construction Enablers are the elements that are employed to move / place Construction Units or regolith. For the present work, this would be the IPEx excavator (below, left), the ARMADAS construction robot (above), and a manipulator + mobility platform for construction using LUNAR-BRIC (below, right).

Modular Properties: The properties of both the Construction Units and Construction Enablers provide estimates of their deployment resource usage. These include standard items such as power, downmass, and volume but would also include characteristics such as positioning accuracy, traverse speed and carrying capacity.

Complementarity of Modules: With the module functionality and properties established, the complementarity between modules can be assessed. There are a multitude of different ways that this can occur (even with only 3 systems being considered), but generically this will establish standard methods for module interface and co-function. Examples of this include: An interface for IPEx to deliver regolith to the LUNAR-BRIC module for bagging; Interface(s) such that ARMADAS can be employed with LUNAR-BRIC for the purposes of mixed construction and alignment.

Mission Analysis: A digital twin environment with the above parameters would be created to study construction scenarios. Operations can be quickly assessed to minimize their power, downmass usage and build time (for example), while maximizing construction volume. Simple physics models could show the efficacy of radiation or rocket blast shielding.

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A Roadmap to Full Autonomy of Lunar Robotic Elements. C. S. Dickinson[1], P. Grouchy[1] and W. Watson[1], [1]MDA, 18050 Saturn Ln #200, Houston, TX (Contact: Cameron.Dickinson@mda.space)

Introduction: Achieving a sustained presence on the lunar surface will require innovations across myriad disciplines, including material and building sciences, power systems, robotics and sensors, and autonomy.

While the need for most of these technologies is self-explanatory, the need for autonomy is more subtle. Clearly, autonomy is not necessary for early proof-of-concept lunar missions that can be accomplished entirely via tele-operation. As we scale our ambitions towards full-scale lunar habitats and eventually the Martian surface, however, autonomy for robotic systems will become in human rated robotics designed to operate without explicit instructions.

For lunar operations, scaling autonomy reduces operational costs and scales capacity towards teamed robotic systems building base camps, landing pads, berms, power sources, and other semi-permanent structures.

While there are hard technological challenges across all of the domains required for a lunar outpost, autonomy is unique in that there are also cultural challenges to overcome: namely human trust in autonomous space systems. To build this trust, the levels of autonomy must be increased gradually, while human involvement is slowly reduced until full autonomy without human oversight is achieved (See [1],[2] & [3] for examples). The more hours of autonomous operation without human intervention that are logged, the more confident ground operators will be in the success of future fully autonomous missions.

The Case for Autonomy: Autonomy for the purpose of Lunar excavation and construction is a necessary element in any sustained Lunar presence. While early efforts could be performed by astronauts, or via teleoperation, these suffer from operational time constraints and bandwidth constraints, respectively.

The question is "*Do we really want astronauts spending their time performing repetitive excavation tasks or using limited lunar bandwidth monitoring repetitive tasks such as excavation?*" Long term the answer to both of these questions is no, particularly in light of the strides that have been made terrestrially in automating similar tasks. Further, as the goals or Artemis extend past Lunar activities to Mars, this will become an absolute necessity given the light delay time for operational communications. With the need for autonomy established, the question switches to how best ot achieve this within all of the mission constraints: most notably while maintaining astronaut safety as well as ensuring lunar infrastructure is not damaged.

The Steps to Full Autonomy: We are proposing that future missions consider adopting the steps outlined below, with the goal of ultimately demonstrating and validating a blueprint for the safe and rapid commissioning of a fully autonomous robotic system for a specific task in a specific worksite by increasing the levels of autonomy from tele-ops to full autonomy.

The three distinct stages of autonomy that a mission (or missions) would be progressed through in series: *Stage 1 – Tele-operations with AI assistance.* In the first stage, control of the robotic systems will be done by human operators on Earth via tele-robotics. Deliberative AI algorithms intended for eventual deployment on the flight hardware will be used to provide planning capabilities on the ground, including suggestions on task planning, arm and rover motion planning, and obstacle avoidance. *Stage 2 – Increasing autonomy with humans in-the-loop.* Here the tasks would be repeated numerous times, transferring more control to the autonomous systems after each iteration, while keeping humans in-the-loop for regular checkpointing and go/no-go decisions. Humans would monitor the execution of the autonomously generated plan, serving as a redundant safety measure, on the road to fully autonomous lunar robotic operations. *Stage 3 – Fully autonomous operations.* Once several iterations of autonomous operations have been completed in Stage 2 without human intervention, fully autonomous operations can be executed to build heritage on the lunar surface.

Conclusion: Deployment of fully autonomous robotic systems is a necessity to meet the goals of Artemis – a long term permanent presence on the moon. This will require a stepwise implementation to both validate the algorithms deployed as well as to build trust with their human operators.

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A Cyber-Physical Testbed for Studying Deep Space Habitat Resilience and Autonomy.

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Introduction: Real-world hardware and complex physical coupling can rarely be perfectly modeled. For that reason, the NASA-funded RETH institute has developed a cyber-physical testbed (CPT). The CPT is one realization of a "smart habitat" (SmartHab), intended to explore the techniques and technologies needed to design and operate an extraterrestrial habitat. The SmartHab has the main subsystems of a deep space habitat, but some are virtual (or cyber), and some are physical. We aim to realistically replicate the physical coupling between the cyber and physical components, when necessary and appropriate, through boundary condition enforcing systems (transfer systems) [1,2].

Problem Definition: The extremely hostile environment present on the Moon includes exposure to hard vacuum, thermal cycles, radition, Moonquakes, micrometeorite impacts, and microgravity. This extreme environment poses many challenged to building a safe environment for habitation. The intention of having this testbed is to not only demonstrate new techniques (fault diagnosis, prognosis, digital twins decision-making, agent action, etc.) but to validate those methods under various conditions and with different subsystems, to examine reproducibility, to understand when those methods may break down, and ultimately to optimize them. By better understanding the limits of the techniques we develop, we can use that knowledge to advance the techniques.

The **physical** subsystems of the CPT in Fig. 1 include: (1) structure; (2) thermal management for the interior environment; (3) thermal effects of the regolith layer and the structure, providing appropriate temperature distribution to the structure using a thermo-mechanical hybrid simulation method we developed, able to individually control the temperature of a boundary of the outer surface of the SmartHab; and (4) limited portions of power and communication subsystems.

Fig. 1 Photo of the physical CPT components.

The **cyber** components include: (1) exterior environment; (2) structural protective layer (regolith assumed, for insulation and radiation protection); (3) inventory; (4) agent subsystem; (5) health management; and (6) the majority of the power and communication subsystems. Note that the cyber components can be modified fairly easily for rapid reconfiguration.

Capabilities: By design, the CPT is less complex than a real system. However, to enable a wide variety of research, we do include the main functions of a space habitat. These subsystems are sized and scaled to have similar dynamics and coupling among subsystems. which will thus allow us to validate our methods on complex systems with modeling errors and other sources of uncertainty. We can introduce several faults independently or in combination, and thus explore diagnostic reasoning, anomaly detection, fault causal models, and root cause determination, etc. The specific hardware can be swapped with alternate components, allowing the CPT to evolve as a testbed for conducting component-in-the-loop experiments. The availability of the CPT allows us to validate techniques such as fault detection, digital twins, continuous updating of models for predicting future behavior or determining time to critical, and decision-making under uncertainty.

Acknowledgment: Based upon work supported by NASA under grant 80NSSC19K1076.

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DEVELOPMENT UPDATE ON PROTOTYPE RECHARGEABLE BATTERIES WITH IMPROVED DISCHARGE CAPACITY AT -40 °C TO -60 °C FOR SURVIVING THE LUNAR NIGHT.

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Introduction: Future science missions to the Lunar surface will require hardware, electronics and energy storage systems that can tolerate the extreme low temperatures of the Lunar night. Some missions will require continuous operation through the night and others will only need to tolerate it and wake up and operate at the Lunar dawn.

The temperatures expected (about -180 °C at night, lower in craters, and up to +120 °C in the day) dictate that batteries and electronics currently must be housed in temperature regulated chambers kept between 0 °C and +40 °C, because this is where lithium-ion cells have adequate performance. Automotive electronics are rated down to -40 °C and military electronics are rated down to -55 °C and it would be advantageous to have rechargeable batteries that could work at least to the same low temperature ranges (either down to -40 °C or -55 °C) to match the limits of existing electronics

Existing Battery Cells: The low temperature performance of lithium battery cells is limited by several factors: (1) the conductivity of the electrolyte; (2) the resistance of the solid electrolyte interface (SEI) or the cathode electrolyte interface (CEI); and (3) the charge transfer resistance of the SEI and/or CEI (moving lithium ions into and out of the solid electrodes). Existing 18650 cells that have > 300 Wh/kg at +20 °C generally are severely limited or non-functional at or below -40 °C.

Advances have been made in fluorinated carbonate liquid electrolytes capable of cycling down to -60 °C or lower [1]. These have been demonstrated on other NASA-funded projects they promote low temperature lithium plating on metal anodes, however improvements in capacity retention at extreme low temperatures (-40 °C to -60 °C) are still of interest when considering the needs of operating electronics in the Lunar day-night cycle.

Solid-liquid interfaces in lithium batteries can suffer from slow lithium ion transfer across this boundary, especially when cold. The typical solution to this problem is to add an ionically conductive additive to form an SEI or a CEI *in situ* during cell formation, or to add an artificial SEI / CEI prior to cell assembly to promote lithium diffusion between electrodes and the electrolyte (and to prevent unwanted side reactions). In many cases the artificial SEI / CEI is a polymer. However, existing CEI/SEI polymers do not perform well in wide temperature ranges. Improved battery operation at extreme temperatures, combined with high specific energy is still critically needed.

Update on New 18650 Cells, Puch Cells and 4S2P Battery Modules in Development: We are developing prototype rechargeable lithium-ion battery cells that operate in extreme temperature environments using a combination of low temperature liquid electrolytes combined with artificial SEI / CEI layers. The combination solves the poor lithium conductivity at the solid-solid interphases in high energy density batteries at -40 °C to -60 °C. The same artificial SEI / CEI also provides some discharge capacity at even -80 °C, but the primary focus of this work is to take full advantage of electronics rated to either -40 °C or -55 °C. Prototype battery cells retain 75% of the room temperature capacity and specific energy when operated at -40 °C (and still maintain close to half of the capacity and energy at $^{-}$60 °C).

Both 18650 cells and pouch cells are being investigated and prepared for technology demonstrations. 18650 cells are being integrated into a 4S2P (10.4-16.8V) flight qualified, protected battery modules with state-of-charge monitoring. These modules will be compatible with existing CubeSat, nanosatellite & small satellite hardware. The initial 4S2P module will be rated to -40 °C (which is the limit of the electronic monitoring chip.) Future versions may be possible for discharge down to -55 °C.

Status: We have an ongoing SBIR Phase II project to develop and test coin cells and pouch cells: we are partnering with battery producers to make 18650 cells. Our battery module partner will will be able to supply either 4S2P (10.4-16.8V), 3S2P (7.8-12.6V) or 2S4P (5.2-8.4V) modules with up to 100Wh of energy and 160 W of power. We are conducting planning activities for tech demonstrations and invite inquires.

Acknowledgments:
NASA SBIR Phase I Contract No 80NSSC22PB215

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[2] US Pat. No. 7,931,824
[3] Additional patents pending

A VLBI AND LASER RANGING CAMPAIGN TO DETECT APOPHIS-FLYBY PERTURBATIONS IN THE ORBIT AND ROTATION OF THE MOON

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Introduction: The small asteroid (99942) Apophis will pass within 38,015 km of the Earth's geocenter on April 13, 2029, and within 95,962 km of the Moon's selenocenter on the following day. Here, we report on a study of the gravitational perturbations caused by this passage through the Earth-Moon system.

The Apophis close approach will reduce the semi-major axis (a) of the Earth-Moon system by $\sim$25 μm, sufficient to increase the Moon's motion by $\sim$3 micro arc seconds (μas) yr^{-1}, assuming an Apophis mass of 6.2×10^{10} kg.) These changes should be observable with state-of-the-art Lunar Laser Ranging (LLR) and Very Long Baseline Interferometry (VLBI) observations of advanced laser retroreflectors [1] and radio beacons [2], if these can be installed before the encounter. A focused campaign to determine the lunar motion around the encounter could both provide a direct determination of the mass of Apophis and demonstrate a new test of lunar rotation theory.

Numerical Determination of Asteroid Perturbations: Our analysis is based on numerical differences of otherwise identical N-body integrations covering the interval from September, 2021, to January, 2042, and including the Sun, the Moon, the Earth and the other 7 planets, together with Pluto, Ceres, Vesta and Psyche and the target body. These were performed using the REBOUND / REBOUNDx integration system [3] with the ias15 integrator and "gr_full" General relativistic 1-PN corrections, together with initial conditions from the JPL Horizons ephemeris and DE440/441 [4].

Earth-Moon Perturbations from the 2029 Apophis Encounter: Even though Apophis is a small object with a relatively small mass, for the assumed mass of 6.2×10^{10} kg differenced REBOUNDx integrations show a total -25.60 μm change in the lunar semi-major axis (a). Through Kepler's law a step function change in a will cause a corresponding rate change in the orbital longitude, l; Figure 1 shows a +1.769 micro arc second (μas) yr^{-1} rate change in l, corresponding to a change in Δl × a of 3.302 mm yr^{-1}.

Estimating Apophis Lunar Perturbations with LLR and VLBI Fiducial Points: The present LLR observing system has sufficed to determine the orbital recession of the Moon to +38.08 ± 0.19 mm yr^{-1} [5], while VLBI has demonstrated the ability to determine (or limit) the proper motions of galaxies and quasars with accuracies of $\sim$1 μas year^{-1} [6, 7].

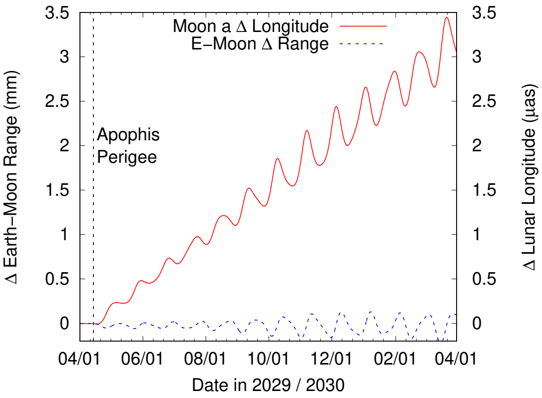

Figure 1: Changes in the lunar orbital radius and orbital longitude, the primary geodetic observables, during the year after the Apophis encounter.

Both LLR and VLBI have geometrical limitations in the constrained dynamics of lunar rotation; LLR directly measures the Earth-Moon radial component, while VLBI is best at determining angular motions, such as lunar longitude rates. We performed simulated solutions with LLR and VLBI data at various points on the lunar surface, assuming LLR normal points from Apache Point [8], and VLBI observations with a subset of the Very Large Baseline Array (VLBA) [9]. Determinations of geometric parameters are much improved through the use of collocated LLR retroreflectors and VLBI beacons (such collocations are of course routine in terrestrial geodesy). If fiducial points are available (e.g., at the planned landing site on Malapert Mt. near the lunar South Pole) it should be possible to observe the Apophis perturbations over a one year observing period.

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Moon Trades: Integrated Autonomous Robotics Systems For Lunar Mining, Tunnelling, and In-Situ Resource Utilization

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Introduction: The goal of Moon Trades' novel lunar mining and tunneling technology is transform lunar resource extraction for both human and robotic astronaut missions by creating a low-mass, low-cost extractor that harnesses the power of AI/ML, augmented reality, and automation to conduct efficient and accurate target acquisition. The advantage of Moon Trades is the integration of VR (Virtual Reality) capabilities into its core hardware which will allow the extraction tool to be operated from Earth or by a spacecraft as if it were being handled at an actual mining site.

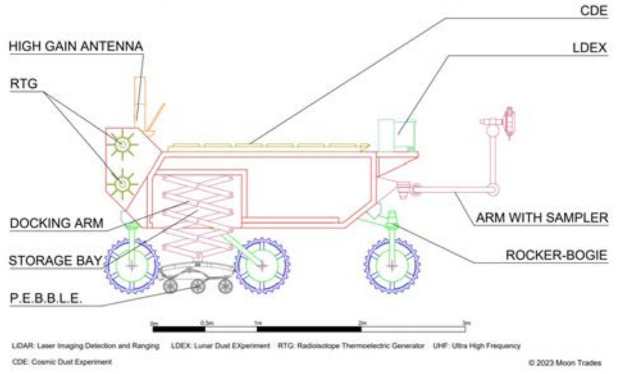

Figure 1. Demonstration of ASTRAL

Moon Trades' primary technology, **ASTRAL:** **A**utonomous **S**pace **T**raversal and **R**esource **A**nalysis **L**ander and **PEBBLE:** **P**lanetary **E**xploration **B**ot for **B**acktracked **L**unar **E**xploration, can be used in extreme environments on Earth and in-space, and combines a series of cutting edge technologies including: virtual reality, regolith sampling using laser spectroscopy, sonar scanning, and high-speed cameras, data analysis, algorithm-based machine learning software, and sample collection into one mechanism.

These mechanisms can be used for autonomous construction, site surveying, reconnaissance, and supplies delivery in-situ for crewed and uncrewed missions, meeting several NASA and ESA goals while providing the space industry with a never before seen approach to site surveying, analysis, and sample collection.

About: Moon Trades is a dynamic international project with an overarching objective of revolutionizing technology within the field of space sciences. Moon Trades is actively engaged in a long-term initiative dedicated to lunar mining and tunnelling. The primary aim of this endeavour is to deploy in-situ autonomous robotics for the excavation of lunar regolith, which will serve as a foundational resource for in-space assembly and manufacturing (ISAM) capabilities. Additionally, the technologies developed by Moon Trades hold potential applications in Earth-based mining projects, further expanding the scope of our contributions to the deep-tech field.

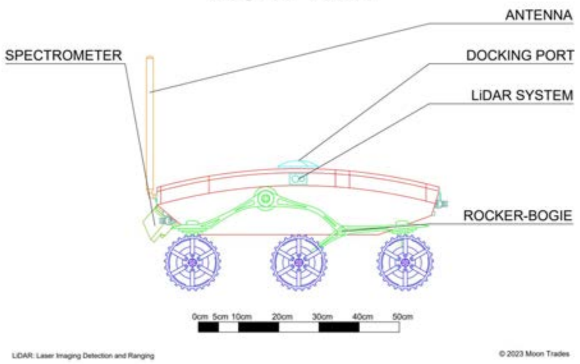

Figure 2. Demonstration of PEBBLE

Moon Trades is currently positioned at a Technology Readiness Level (TRL) 2, signifying that we have developed a well-rounded use case to support our early stage R&D in our technological development journey. At this juncture, we are deeply engaged in collaborative efforts with subject matter experts, successfully defining the critical milestones integral to the prototype development process. This collaborative approach ensures that our technological endeavors align seamlessly with the needs and expectations of the aerospace and space sciences sectors in both the government, academic, and private sectors.

Since the birth of these agreements, a concrete direction of study and design of the Moon Trades technology has been developed such that it can operate with a high certainty and levels of acute accuracy in the race for the extraction of raw materials on the lunar soil and the development of increasingly concrete technologies regarding the environmental feasibility of extreme environments.

Learn more about Moon Trades by visiting: **moontrades.org**

Exploring Technologies For ISRU and Lunar Manufacturing Of Regolith Structures:

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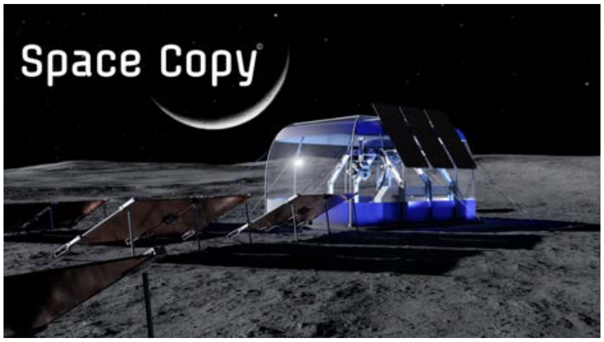

Figure 1. Demonstration of hardware

Introduction: The goal of Space Copy's additive manufacturing technology is to leverage selective laser melting (SLM) technology and Raman spectroscopy to design a novel multipurpose manufacturing and material characterization device for infrastructure development using regolith.

Space Copy's hardware is capable of identifying the chemical composition of lunar regolith samples, develop a viable feedstock using low-energy beneficiation methods, and utilize in-situ resources to 3D print the supplies needed to sustain a lunar habitat, ranging from precision tooling, repair parts, launchpads, and bricks.

Space Copy's technology process is currently measured at TRL 3, with lunar analog testing of coupons scheduled for 2024. The integration of a customized AI-powered machine learning operating system that is responsible for autonomous functionality and data transfer for continuous optimization.

Space Copy is capable of functioning in extreme environments on Earth and in space, producing robust components for applications in aerospace, defense, and construction. The primary geometries that Space Copy will manufacture are:

- Interlocking Bricks
- Precision Tools
- Repair Parts
- Piping
- Heat Shields

Space Copy is introducing a novel additive manufacturing and material characterization device that can be deployed for use in extreme environments on Earth and space in order to sustainably create infrastructure from regolith or terrestrial-based soil. This technology will enable the rapid, low-risk prototyping of repair parts, precision tooling, interlocking bricks for habitats and roadways, industrial piping, and more using Selective Laser Melting (SLM) in a vacuum.

Figure 2. BP-1 Simulant (Left) and LHS-1D (Right) Bricks from FDM and Binder Jetting

With lunar environment simulation testing scheduled for 2024, the LUMINAR prototype: the **L**unar **U**tilization for **M**anufacturing **I**n-Situ with **N**ano **A**ssembly and **R**aman spectroscopy, aims to reduce the cost and frequency of lunar service missions, and well as reduce the amount of pollution and debris emitted by continuous resupply payloads sent to the lunar surface to sustain long-term human presence.

Space Copy, operates in various phases to combine high energy spectroscopic analysis for parameter optimization and chemical diagnostics, in conjunction with beneficiation of small to medium sized particulate for effective particle size distribution to be utilized in a novel Selective Laser Melting (SLM) process that operates in vacuum conditions with consideration of mitigating the challenges associated with microgravity, external radiation, and porosity of prints. Combining materials science with robotics, and near real-time tele-operational capabilities, ensures near-continuous interaction with lunar hardware from Earth, delivering seamless manufacturing, qualification, and process optimization through direct communication with terrestrial-based operations during the initial operational period. The future development of lunar hardware for regolith-based manufacturing holds potential for both crewed and uncrewed missions.

Learn more about Space Copy by
visiting: **spacecopy.com**

Exploring Time-Sensitive Networking for Enhanced Lunar Communication: Onboard Networks and Integration with MRR-Based Passive Optical Wireless Architecture.

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Introduction: Future lunar surface exploration will benefit greatly from a comprehensive, wide-bandwidth, and reliable communication network in the cis-lunar region. The integration of Time-Sensitive Networking (TSN) into this network is needed for real-time applications such as positioning, navigation, and timing (PNT), co-ordinated and co-operated autonomous vehicles, time-critical safety operations, distributed interferometric radar sensing and radio telescopes, etc. TSN provides advanced capabilities in terms of timing deterministic and bounded low-latency network services within and between lunar orbiters, Gateway, surface habitats, rovers as well as fixed surface infrastructures. Passive optical wireless linking architecture with modulating retroreflectors (MRR) may provide complementary connectivities to the existing LunaNet architecture, enabling distributed Internet-of-Thing-like sensors and nodes to be deployed on the lunar surface featuring ultra-low power consumption and long operating lifetimes. This paper explores a TSN-integrated network standard with the IEEE 802.1AS protocol for the LunaNet communication architecture enhanced by MRR-based passive optical communications.

Communication System: The scenario under consideration involves a few orbiters equipped with interrogator beams and a swarm of surface assets distributed across the lunar surface. The interrogator laser beams onto the devices within the swarm. These laser beams are then reflected off the MRRs integrated into the lunar surface assets and captured by the interrogators. Each device within the swarm can emit a distinguishable beacon on the laser carrier, enabling the interrogator to identify the specific device and its corresponding orientation for communication purposes. Importantly, the chosen architectural framework intentionally excludes direct interconnections among swarm devices. In this scenario, the goal is to implement a TSN intra-communication network. The current solutions face limitations in handling gigabits of data generated by new instruments and equipment. Upgrading to a gigabit-capable network would enable satellite users to efficiently manage large volumes of raw data. Additionally, the existing bus systems, primarily utilized in the satellite industry, pose high costs in terms of development and updates. To address this, integrating Commercial Off-The-Shelf (COTS) technology is considered. Collaborating with other industries, such as automotive and aeronautics, could lead to shared advancements and cost reductions. The onboard transmits essential information to ensure the nominal functioning of the satellite and handle the data produced by payload instruments. It facilitates the transmission of data from various sources, including sensors, and manages critical tasks such as flight control commands. This specific type of traffic, often referred to as time-critical traffic, demands communication with bounded latency and minimal jitter. By integrating TSN, the internal devices interconnected synchronize using the IEEE 802.1AS protocol and through a message scheduling scheme, TSN enables achieving bounded latency and minimal jitter. The optimization problem for scheduling in aerospace applications has been formulated and described [1], in this work, it is specifically applied to the internal network of orbiters employing laser beams. Furthermore, the potential extension of TSN connectivity between orbiters and the swarm of assets is being assessed, intending to achieve synchronization among the vehicles of the swarm using the TSN synchronization standard. This study initiates, for the first time, an analysis of how the modulating retroreflecting physical layer influences the performance of TSN within the envisioned optical communication system.

Conclusions: The adoption of Time-Sensitive Networking for the upcoming lunar spacecraft onboard network aligns with stringent performance requirements, as shown by the performance evaluation. The performance has also been assessed including a comparison with state-of-the-art solutions. Furthermore, an investigative analysis has been conducted to explore the extension of TSN connectivity between orbiters and the swarm of assets, strategically leveraging the modulating retroreflecting physical layer.

References: [1] Fiori, Tiziana, et al. *IEEE Access* (2024).

Numerical Modeling of Electrodynamic Dust Shielding for Lunar Dust Mitigation. R. Fonteyne and Á. Romero-Calvo, Georgia Institute of Technology. (Contact: rfonteyne3@gatech.edu).

Introduction: The renewed interest in lunar dust is closely tied to the upcoming Artemis era, which aims to return humans to the Moon. Lunar dust, known for its ultrafine, abrasive characteristics [1-2], and its propensity to adhere to a wide range of surfaces [2], represents a significant hazard to both lunar equipment and astronauts [3-4]. In the realm of lunar exploration, various dust mitigation technologies have emerged as crucial for safeguarding both equipment and astronauts [5]. Among these, the electrodynamic dust shield (EDS) – which uses electrostatic and dielectrophoretic forces to repel dust particles – has gained prominence as a promising solution due to its dust mitigation capabilities.

In response to these challenges, research has been initiated to refine electrodynamic dust shield models, aiming to enhance our understanding of the design space of the system. The objective is to enrich our understanding of the EDS's efficiency, particularly in the harsh lunar environment where the irregularity of particles is a pivotal factor in shield performance, as well as to provide a comprehensive overview of the initial model developed. This overview includes a discussion on both the opportunities and challenges presented by the current state of knowledge, offering insights into the EDS mitigation strategy's potential and its effectiveness against lunar dust. Additionally, it sets the stage for future research focused on the simulation of the lunar plasma sheath and the variable charge of particles contingent on current.

Methodology: Electrodynamic Dust Shielding (EDS) leverages electrode technology alongside the generation of a non-uniform electric field to effectively transport dust particles. Current research in this area includes simulating a bi-phase non-uniform electric field, coupled with the trajectory computation of spherical particles [6]. While these models have achieved significant accuracy in mirroring real-world outcomes, they often overlook crucial lunar surface conditions. Spherical particles, which these models typically assume, are rarely encountered on the lunar surface. Additionally, current models do not adequately account for the Moon's reduced gravity, its complex plasma sheath, and the time-varying particle charges. Consequently, our research pivots to concentrate on a more complex and realistic scenario involving non-spherical particles lofting in a reduced gravity environment.

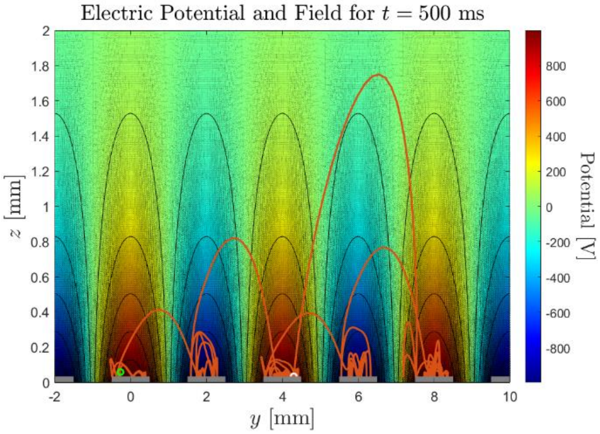

Fig. 1: Dust particle trajectory under the effect of a non-uniform electric field. Display of the initial (white circle) and final (green circle) positions.

Through numerical integration of a charged particle's motion, it is possible to derive velocity profiles and trajectories, dependent on the particle's initial position and the EDS's angle. Leveraging the capabilities of non-spherical harmonics, it is possible to delineate the force-induced motion of an aspherical particle, offering a nuanced contrast to the traditional single-spherical particle paradigm through the innovative patched-charge model. Consequently, our team is formulating a model that melds computational strategies to accurately simulate the behavior of dust particles of varied shapes within the EDS's electric field. The simulations demonstrate that asphericity significantly affects the exerted forces (e.g., dielectrophoretic force), and thus the EDS's ability to repel particles.

Acknowledgements: This work is supported by the NASA Solar System Exploration Research Virtual Institute (SSERVI), under cooperative agreement number NNH22ZDA020C (CLEVER). Grant number: 80NSSC23M022.

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ZIN Technologies' Lunar Surface Capabilities. Michael Johanson, Senior Vice President of Business Development and Strategic Planning. johansonm@zin-tech.com. 6745 Engle Rd, Cleveland OH, 44130

Introduction:

ZIN Technologies (ZIN), a wholly owned subsidiary of Voyager Space Holdings, is an experienced AS9100D and ISO 9001:2015 certified small business provider for a range of products, multi-disciplined engineering services, and manufacturing capabilities that support numerous microgravity, deep space, lunar, and martian missions and are easily designable, integrateable, and implementable to Lunar Surface Innovative Consortium's (LSIC) mission, goals, and stakeholders. ZIN has the potential to support lunar surface missions, technologies, and operations

Clear Dust Repellant Coating (CDRC):

CDRC, also known as Novel Durable Silica-based Transparent coating (NoDuST), was a NASA SBIR Phase I completed by Voyager subsidiary Pioneer Astronautics and is currently developed at ZIN. NoDuST is a silica-titania based coating that can be used to prevent regolith from adhering to optical and mechanical components such as solar cells, camera lenses, actuators, and hinges that operate in dusty lunar conditions. The NoDuST coating passively minimizes dust adhesion by reducing adhesion forces between the coating and lunar regolith particles. This coating has additional benefits compared to similar ones used in terrestrial applications: it has increased hardness to withstand operation in lunar conditions with sharp particles comprising lunar regolith, it is clear to visible light and suitable for applications requiring visibility of the surface covered with these from fading and degradation, and has a potentially increased resistance to degradration caused by space radiation. [1] The coating is currently at TRL 6 and supports various experiments that are ready for lunar exploration.

Power Management Systems:

ZIN develops various power systems that support vital in-space power applications for several key missions. ZIN created three electrical power system line replaceable units (Low/High Voltage Power Distribution Units, Power/Payload Power Converter Units) that will fly on the upcoming unmanned Sierra Space Dream Chaser® winged spacecraft. ZIN's electrical power system hardware controls the distribution and power conversion for the entire Dream Chaser spacecraft.

ZIN also designed, built, and tested the Power Processing Unit for NASA's Evolutionary Xenon Thruster-Commerical (NEXT-C) ion propulsion technology successfully flown on NASA's Double Asteroid Redirection Test (DART) mission. This flight heritage gave ZIN the opportunity to create an upgraded PPU for US Space Force Advanced NEXT (AdvNEXT) mission. The NEXT Power Processing Units demonstrate ZIN's ability to perform high-voltage, radiation-hardened DC-DC conversion that is directly applicable to Lunar power system goals. With these technologies, ZIN has the capability to provide efficient-proven power to the lunar surface, whether through lander, surface power, ISRU, or rover missions.

Radiation-Hardened Electronics:

ZIN is experienced in selecting space-grade, radiation-hardened electronics in our past performance. ZIN's manufacturing facilities build hardware and electronics that have proven flight effective on previous and upcoming cislunar and deep space missions. This capability can be aligned to lunar surface missions that require survival in extreme environments.

Space & Lunar Communications:

ZIN provides SATCOM services and solutions to support the commercial industry growth with an ever declining NASA TDRSS system. ZIN's position can help maintain and improve the LEO satellite network and eventually lunar orbiting satellites. ZIN has also submitted a proposed DARPA Luna-10 study for lunar surface communications relay & power station tower with Northeast Ohio partner Comsat Architects that can establish an early communication route to future lunar surface technologies in the south pole region.

CLPS Support:

ZIN currently supports Ceres Robotics as a major subcontractor on upcoming CLPS and/or lunar rover solicitations. This partnership allows for ZIN to provide manufacturing capabilities, thermal, communication, and power analyses to their proposed B5 lander design.

References:

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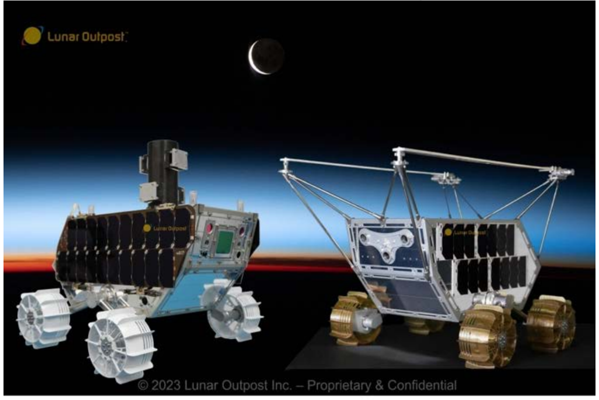
From Exploration to Infrastructure and Beyond: Scalable Lunar Mobility as a Service.

A.J. Gemer[1], J.A. Cyrus[1], J.B. Cyrus[1] , and F. Meyen[1], [1]Lunar Outpost Inc, 12555 W. 52nd Ave, Arvada CO 80002, (Contact: AJ@LunarOutpost.com)

Introduction: Robotic assets on the lunar surface are advancing rapidly, providing increased opportunities for scientific and commercial payloads to engage with the lunar environment in ever more interactive ways. Many of these payloads benefit greatly from mobility capabilities, maximizing their science data return and commercial viability. The commercial lunar mobility services market is responding to these payload-driven needs by providing increased mass, power, and data capabilities, along with unique rideshare and service-based pricing models to allow greater flexibility and access to lunar sites of interest for the widest range of lunar payload users.

Lunar Outpost's first mission, Lunar Voyage 1 (LV1), is set to launch a Mobile Autonomous Prospecting Platform (MAPP) rover aboard the Intuitive Machines IM-2 lander in 2024; this mission carries 9 commercial payloads, providing technology demonstrations, TRL advancement, and valuable data about the lunar South polar environment. Lunar Voyage 2 (LV2) is a NASA-funded science mission to Reiner Gamma, providing mobility to the JHU APL PRISM-1a Lunar Vertex science instrument suite. Both LV1 and LV2 Flight Model (FM) MAPP rovers are shown in the image below.



Lunar Voyage 3 (LV3): Following the successful deliveries of the LV1 and LV2 FM MAPPs, Lunar Outpost is currently developing another commercial mission for 2025. This mission will again provide opportunities for industry, academic, and science payloads and instruments to access the lunar surface, gain operationally-useful heritage and data, and contract mobility services. Payload space is still available aboard the LV3 MAPP.

ASA Trailblazer: The Australian Space Agency (ASA) has launched the Trailblazer initiative under its Moon to Mars program to develop new capabilities in the Australian space sector, including foundation services for lunar exploration missions. The initiative aims to demonstrate and progress Australian exploration capabilities with remotely operated and autonomous Australian robotic lunar assets, contributing to NASA's Artemis program. The Consortium led by Lunar Outpost Oceania has been selected for the development of a foundation services rover platform capable of collecting lunar regolith and delivering it to a NASA in-situ resource utilization facility. Lunar Outpost Oceania will be working with a consortium that includes EPE, BHP, RMIT University, the University of Melbourne's Space Laboratory and others to develop the rover platform.

Infrastructure Robotics: Beyond the aforementioned exploration and technology demonstration missions is medium- to large-scale lunar surface operations, including infrastructure establishment and maintenance, and bulk regolith handling for excavation, construction, and ISRU. Lunar Outpost has demonstrated these capabilities through competing in the NASA Break the Ice Challenge, delivering 12 tons of icy lunar regolith simulant a total of 120 km over 15 days of operation (image below). Lunar Outpost is also leading a NASA STTR effort with Michigan Technological University to develop the REGOWorks Lunar Civil Engineering software toolkit, in preparation for future large-scale robotic lunar infrastructure missions.

Mars to Moon, Bringing Helicopter Technologies to Lunar Applications.

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Introduction: Aerial mobility on Mars requires power-efficient and lightweight hardware with sufficient computational resources to run onboard control algorithms. The design-driver of operating in the thin Marian atmosphere results in architectures and systems with cross-cutting applications. Technologies with relevance to the lunar environment are the miniature manipulator, lightweight mobility system, and the TubeBot platform.

The miniature manipulator and lightweight mobility systems were developed as part of the Mars Recovery Helicopter (SRH) concept developed for the planned Mars Sample Return (MSR) campaign. These developments are both part of the Surace Robotics Subsystem (SRS), enabling for a coupled robotic solution for picking up and dropping off sample tubes.

TubeBot is a miniature, self-contained platform designed to host up to 250-gram payloads. With standardized interfaces, reliable avionics, and an independent telecom link, it presents a new low-cost approach to access planetary surfaces. Similar to CubeSats, there are multiple possible size scales with the smallest being small enough to be flown by SRH on Mars with similar interfaces as the sample tubes currently on Mars. Larger sizes can support additional batteries, S-band radios capable of relaying data to orbiting spacecraft, and thermal management to survive the lunar night.

Technology: The arm is a three degree of freedom rotary planar arm. The gripper utilizes two individually actuated sets of complainant fingers (4 total fingers). The gripper enables ground plane compliance and rock shedding. The manipulator and gripper have a combined 150 gram current best estimate (CBE) mass. The 4-wheel skid steer mobility system has a 100 gram CBE mass. The designs have completed a Preliminary Design Review (PDR) and an integrated autonomous prototype demonstration with flight-like cameras and processor. The combination of 6 mm and 8 mm brushless DC motors and custom gearboxes that enable the arm, gripper, and mobility system have completed life testing across temperature.

TubeBot, currently in development, draws from innovations in Ingenuity & SRH avionics, battery technology, and telecom systems. This heritage results in a system with expected standby power of <1 μW, batteries capable of being flown at a zero-state-of-charge, and dual radios capable of 900 MHz, UHF, and S-Band communications. At its smallest, by only using the 900 MHz radio and a single 18650 battery cell, the TubeBot system will have a mass less than 200 grams, including 30g reserved for payloads.

Safety and simplicity are key advantages of the TubeBot platform that enable simple deployments as part of larger missions. Since deployment can be as simple as spring ejection or release into the regolith, and safety is guaranteed through redundancy, mechanical interlocks, and fault-protection, TubeBots can augment larger missions.

Applications: For lunar applications, the manipulator and mobility systems could be utilized for precision placement of onboard miniature instruments such as APXS or Raman spectrometer. It could be used to deploy miniature sensors such as seismometers or Mossbaurer instrument.

TubeBots can be placed or positioned by robotic arms, or energetically released to enable either careful placement of scientific sensors, or easy access to impassible terrain such as permanently shadowed regions. TubeBot is a platform designed to be able to host a wide range of possible payloads. Several options of interest include seismometers, a regolith penetrometer, dust mitigation experiments, plume modelling by pairing particle counters with an active source, and deployed navigational aids or telecom repeaters.

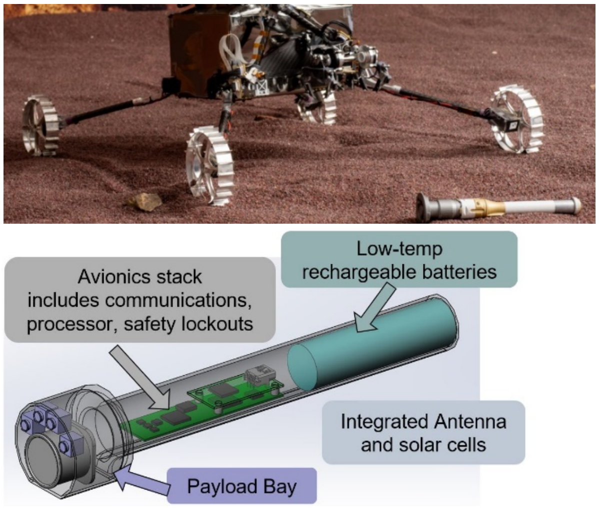

Figure 1: The miniature manipulator and lightweight mobility system, capable of ferrying sample tubes (TOP). The smallest TubeBot is small and light enough to be flown by SRH (Bottom).

Automated Reconfigurable Mission Adaptive Digital Assembly Systems (ARMADAS): Progress Towards Robotic Outfitting of Lunar Infrastructure.

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Introduction: The Automated Reconfigurable Mission Adaptive Digital Assembly Systems (ARMADAS) project at NASA Ames Research Center is developing autonomous infrastructure, instrumentation, and spacecraft assembly and manufacturing capabilities for next generation exploration and science missions, with a goal to change the cost scaling of these missions relative to mission size and duration. Using a building-block approach with a 'kit of parts' composed of ultra-light, high-performance mechanical metamaterials, simplified robots leverage the period environment to achieve high levels of autonomy and reliability for in-space and surface assembly of large-scale apertures, solar-arrays, towers, habitats, and other infrastructure. Robots and structure break down into a compact form factor for launch. By leveraging economies of scale and achieving high-packing ratios, ARMADAS technology can revolutionize space missions by breaking the tyranny of the launch shroud, decreasing development times, decreasing mission costs for transformative science capability, and providing a scalable and versatile space infrastructure strategy. An ecosystem of reconfigurable infrastructure modules can be reused, repaired, expanded reconfigured to meet emergency or unforeseen needs, and reduce spare parts.

Capabilities: To date, the ARMADAS project has demonstrated autonomous assembly of hundreds of structural modules into a meters-scale structure in an earth gravity environment (Figure 1)[1]. The mechanical performance is on par with conventional space structures, at a fraction of the cost. By using highly repeatable manufacturing processes (injection molding carbon fiber reinforced space-rated polymers), the structures are both cost effective and highly precise. The ARAMADAS system carefully designs parts for high-precision assembly–the simple and cost-effective robots build structures much larger and more precise than themselves. While maintaining structural efficiency, the ARMADAS system encompasses many functional module types, including for solar power, comm/power routing, etc., that will enable entire infrastructure systems to be engineered and autonomously assembled with modular parts. With well-defined interfaces, custom instrumentation modules can easily be added to fit many mission objectives.

Figure 1. Laboratory demonstration of autonomous assembly.

Lunar Infrastructure Vision: At the LSIC 2024 spring meeting, we will present updates on implementation of the ARMADAS vision for a general-purpose lunar construction kit capable of meeting a wide variety of lunar surface infrastructure needs (Figure 2). We present various updates on outfitting of our structures, including solar, footer modules, rail, and power/cable-routing. Footing modules will allow infrastructure construction at locations with no surface preparation. Footer, primary structure, and rail modules can create reconfigurable rail systems. These rail systems can be used to reduce cost-of-transport between frequently accessed sites, provide dust mitigation, and convey power and communications. High-performance structure modules combined with power-routing and solar modules can create tall towers for power and communication. Concepts for habitats and garages can support regolith cover. This system can be leveraged by many in-situ resource utilization (ISRU) technologies to simplify processes and augment capabilities.

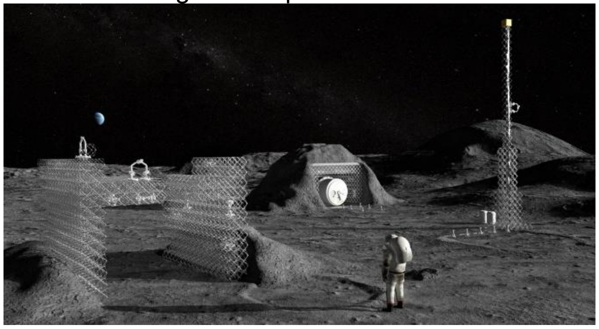

Figure 2. Concept art depicting how a small set of general ARMADAS structural module types and construction robots can meet a wide range of infrastructure needs, including towers, ISRU integration, and habitats/garages.

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[1] C. E. Gregg et al., “Ultralight, strong, and self-reprogrammable mechanical metamaterials,” Sci. Robot., Jan. 2024, doi: 10.1126/scirobotics.adi2746.

A Fully Automated, Demonstration Scale Carbothermal Reactor. N. P. Haggerty[1], B. C. White[1] and A. J. Paz[2], [1]Sierra Space,1212 Fourier Drive, Madison WI 53717, [2]NASA Johnson Space Center, 2101 NASA Parkway, Houston TX 77058, (Contact: Nathan.Haggerty@sierraspace.com)

Introduction: Oxygen constitutes the bulk of propellant mass. Obtaining oxygen in-situ enables lunar commercialization through dramatic reduction of the mass costs associated with lunar launch and landing. One method to extract oxygen from lunar regolith is carbothermal reduction [1]. Sierra Space has tested a flight forward Carbothermal Oxygen Production Reactor (COPR) under ambient conditions and will test it in a thermal vacuum chamber in June 2024 through NASA's Carbothermal Reduction Demonstration (CaRD) program. Afterwards, the CaRD program will integrate the COPR reactor with a solar concentrator, optical shutter, gas analysis system, avionics, software, and additional ground support equipment for an integrated system test in late 2024. The CaRD project aims to increase the Technology Readiness Level (TRL) of a combined solar concentrator and carbothermal reduction system.

Scalable Flight Forward Architecture: The COPR reactor demonstrates a mass efficient, scalable architecture sized for a lunar demonstration mission. A previous Carbothermal Oxygen Production (CTOP) program demonstrated a carbothermal architecture capable of mass production of oxygen from lunar regolith simulant [1]. The technologies that enabled mass production of oxygen were miniaturized from the CTOP program and integrated into the COPR reactor. This results in a mass efficient design that demonstrates the technologies required for high-rate oxygen production.

Direct Energy Approach and Thermal Control: The COPR reactor uses a direct energy processing approach where concentrated light is applied directly to the lunar regolith simulant surface, using the insulating material properties of the regolith simulant itself to separate the molten material from the reactor walls. This approach allows for a completely passive thermal control system where high temperature (>1800°C) carbothermal processing is performed without requiring exotic materials or complex cooling systems. Additionally, by using the direct processing approach, the reactor simply starts and stops the carbothermal reduction reaction by applying or removing the incoming concentrated solar energy.

Automated Material Handling:

The COPR reactor includes an end-to-end automated solid material handling system including metering the lunar regolith simulant from a hopper into a pressurized volume, weighing it, distributing it within the reactor and removal of the deoxygenated slag. Additionally, the automated systems can remove all the material from the reactor to test alternate regolith sources on a lunar mission. In January and February 2024 Sierra Space demonstrated repeated, automated material handling processes in the presence of lunar regolith simulant.

Ambient Ground Testing Results: In January 2024 the COPR reactor was integrated with a commercial version of NASA's flight rated Mass Spectrometer Observing Lunar Operations (MSolo) instrument. The MSolo instrument measured the carbon monoxide produced by the COPR reactor and was compared to the Sierra Space gas chromatograph (GC). This testing showed an average relative accuracy to the GC of 7.91% ± 4.13%, up to 20.3 grams of oxygen produced per kWh of thermal energy input and up to .218 kg of oxygen per kg of lunar regolith simulant used.

Gas Processing: Sierra Space completed a CDR for a flight forward gas processing system to drive the carbothermal reactor in December 2023. This system includes the valves, flight forward regulator, sensors, and a Methanation reactor to convert the carbon monoxide produced by the carbothermal reactor into water. This fluid system will drive the carbothermal reactor inside the thermal vacuum chamber.

References:

[1] White B. C. and Haggerty N. P. (2023) Carbothermal Reduction System Overview and Developments in Support of the Artemis Program and a Commercial Lunar Economy. In *52nd International Conference on Environmental Systems*.

Particle Swarm Optimization for Optimal Sizing of Microgrids in Space Exploration Contexts

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Introduction: For the last few years, there has been a growing interest in implementing microgrids for space exploration purposes. In this case, optimizing the microgrid design is important to determine the optimal sizing of microgrid components and devices. Heuristic algorithms are the most frequently employed techniques to select the optimal sizing of the microgrid components. In this research, Particle Swarm Optimization (PSO) is used for optimal sizing of microgrids [1]. According to the literature, solar power is the main energy source in low-atmosphere environments. Moon's rotational period to the sun is about 29.5 Earth days (708 hours) [2]. To support the load during the long night hours, an efficient energy storage system is required. As space missions need to be self-sufficient due to their intrinsic remoteness, optimal microgrid sizing can ensure a consistent and sufficient power source for the space mission's duration, eliminating the need for resupply. Moreover, the weight and size of the power system component in the space mission can be decreased by properly sizing the microgrid components.

Data Collection: The number of solar panels and batteries for the energy storage system is selected based on the power requirement and load profile in space. Fig. 1 shows the combined electric load profile during one astronaut day in space (24 hours). This load profile includes life support load, housekeeping load, monitoring load, etc. [3]. Solar temperature varies between -127 ℃ to +173 ℃ on the moon's surface [4]. In this study, the temperature data for the solar energy generation profile was generated within this range using Gaussian distribution. A similar method was followed for solar irradiance data.

Discussion: The load, solar energy generation, battery charging, and discharging profiles are shown in Fig.2. In the simulation, initially, the solar energy generation (green line) is less than the load demand (red line). That's why, the battery discharges, which is shown by blue colored line. Whenever the solar energy generation is higher than the load demand, the battery starts charging, which is shown by cyan colored line. According to the simulation, to fulfill the considered load profile, the required optimal size of the solar panel is 32KW (total rated power) and the required minimum battery size is 6700 KWh. The microgrid sizing method suggested here is versatile and suitable for configuring microgrids in the context of space exploration. In future, more research will be conducted in the input data selection section and efficient storage system.

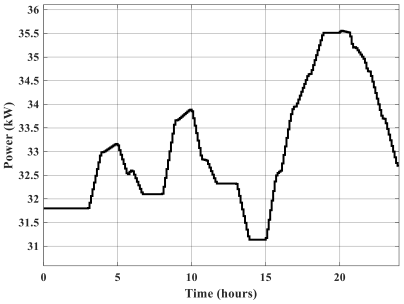

Fig.1. Typical load profile during one astronaut day (24 hours).

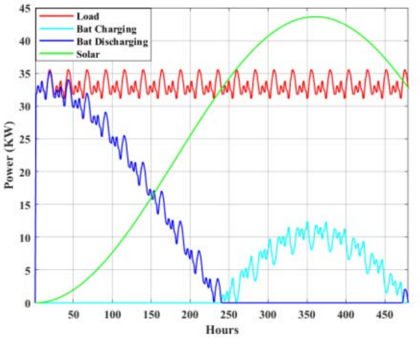

Fig. 2. Load, solar, battery charging, and discharging characteristics for the selected residential load profile.

References:

[1] B. Li, R. Roche, and A. Miraoui, "Microgrid sizing with combined evolutionary algorithm and MILP unit commitment," Appl. Energy, vol. 188, pp. 547–562, 2017.

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[3] Chebbo, Leila, et al. "Modeling and Operation of Microgrids for Deep Space Habitats Under Environmental Disturbances." 2023 IEEE Power and Energy Conference at Illinois (PECI). IEEE, 2023.

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Particle Swarm Optimization for Optimal Sizing of Microgrids in Residential, Industrial, and Space Exploration Contexts

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Abstract: For the last few years, there has been a growing trend in the use of microgrids for residential, industrial, and space exploration purposes. To reduce carbon emissions and dependence on fossil fuels, it is essential to increase the utilization of clean energy microgrids. Moreover, optimization in microgrids is important to determine the optimal sizing of microgrid components, such as solar panels, wind turbines, and storage devices. Heuristic algorithms are the most frequently employed techniques to select the optimal sizing of the microgrid components. In this research, Particle Swarm Optimization (PSO) is used for optimal sizing of microgrids. The number of solar panels, wind turbines, and batteries as energy storage devices, are selected for typical residential and industrial load profiles. The proposed methodology and optimization technique has been substantiated by utilizing HOMER Pro and MATLAB software. The microgrid sizing method suggested here is versatile, suitable not just for residential and industrial settings, but also for configuring microgrids in the context of space exploration. As space missions need to be self-sufficient due to their intrinsic remoteness, optimal microgrid sizing can ensure a consistent and sufficient power source for the space mission's duration, eliminating the need for resupply. Moreover, the weight and space needed for microgrid components in the space mission can be decreased by properly sizing the microgrid to ensure that the system is as efficient as possible in terms of energy production and storage.

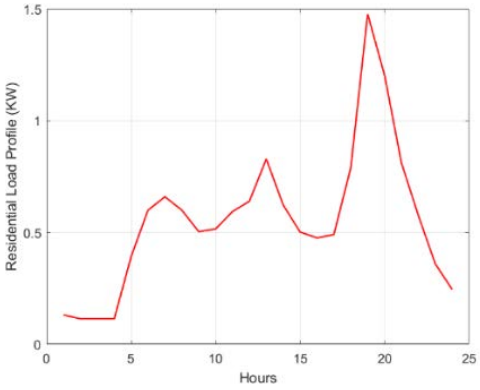

Fig.1. Load profile of a typical residential load for a single day (24 hours).

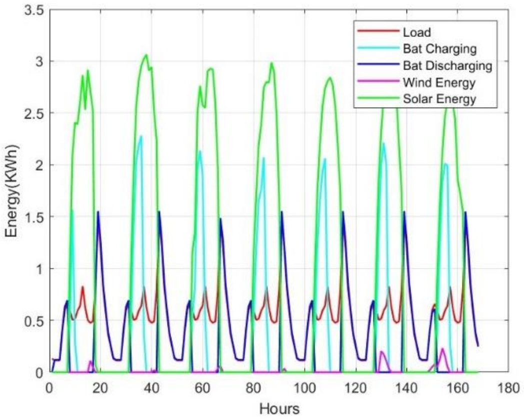

Fig. 2. Load, solar, wind, battery charging, and discharging characteristics for the selected residential load profile (for 1 week).

[The optimal number of solar panels, wind turbines, and batteries for the selected residential load profile is 4, 1, and 3 respectively. For industrial load and space exploration microgrid sizing, the selected load profile should be replaced with the respective load profiles]

References:

[1] J. Li, W. Wei, and J. Xiang, "A simple sizing algorithm for stand-alone PV/Wind/Battery hybrid microgrids," Energies, vol. 5, no. 12, pp. 5307–5323, 2012.

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[4] R. Atia and N. Yamada, "Sizing and Analysis of Renewable Energy and Battery Systems in Residential Microgrids," IEEE Trans. Smart Grid, vol. 7, no. 3, pp. 1204–1213, 2016.

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Mechanical Characterization of Sintered Lunar Regolith Simulants for Extraterrestrial Construction. J. E. Ryu[1] and A. G. Hannon[2], [1]Assistant Professor-Department of Mechanical and Aerospace Engineering, North Carolina State University, 1001 Capability Drive, North Carolina State University, Raleigh, NC 27695, [2]Student-Department of Mechanical and Aerospace Engineering, North Carolina State University, 1001 Capability Drive, North Carolina State University, Raleigh, NC 27695. (Contact: aghannon@ncsu.edu)

The construction of a moon base is an imperative step in humanity's evolution in space exploration. Such a base not only serves as a precursor to future extraterrestrial colonization but also offers numerous benefits, including reduced gravity for launches and opportunities for extensive lunar exploration. In situ resource utilization addresses a major challenge in space missions: the impracticality of transporting all construction materials from Earth due to weight limitations of spacecraft. We propose using lunar resources, specifically regolith, for building, leveraging binder jet printing (BJP) and sintering techniques. In this study, we aim to determine how binder jet printing and different sinter conditions influence the impact resistance and tensile strength of produced structures. Using differential scanning calorimetry (DSC) we will first determine both the glass transition temperature and the melting temperature of the simulants. This data will allow us to form hypotheses of the optimal sinter conditions. The regolith simulants, blended with a commercial BJP system's binder, undergo molding, oven-drying, and subsequent sintering to form the samples. Tensile (ASTM C1273-18) and impact testing of the finished samples will provide insight into the performance of the simulants and the different sinter cycles. This study contributes to the broader vision of space exploration by leveraging in-situ resources for construction purposes.

Modeling Timing Uncertainty in Cislunar Space using GPS Time Transfer.

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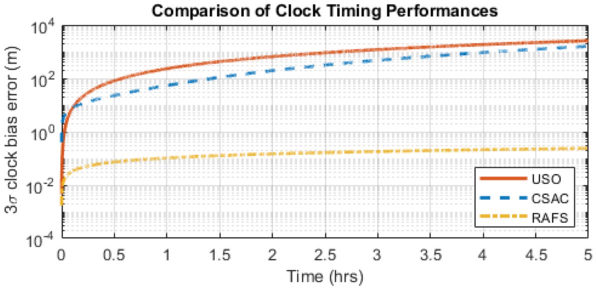
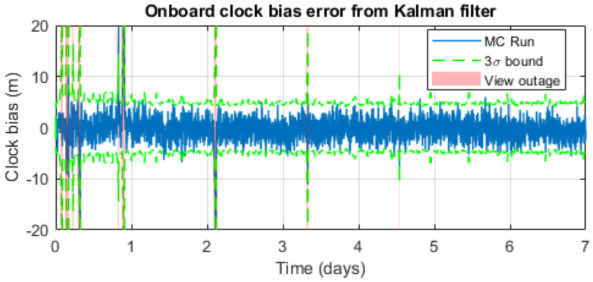
Introduction: Planned robotic and human presence in cislunar space is creating a need for reliable, scalable navigation solutions and timekeeping. As such, several organizations (NASA and the ESA included [1,2]) have made plans for the establishment of a lunar navigation satellite system (LNSS). Earth GNSS utilizes ground-based stations to track and correct satellite clocks; in cislunar space, this is complicated by distance and more challenging communications. The reception of weak GNSS signals and use for time transfer are currently being explored for lunar distances [3]; the work presented here explores this technique in the context of minimizing timing uncertainty in a LNSS implementation. Such techniques can also be utilized on standalone missions requiring high timing accuracy.

Clock Selection and Modeling: Zucca and Tavella [4] provide a compact representation of oscillator evolution over time as a random walk- and run-type process given by system of linear equations; a second-order Gauss-Markov process can be used for stability under longer observation periods [5]. Statistics characterizing Allan or Hadamard variance is typically provided in oscillator datasheets and can be used to characterize clock uncertainty over time. In this research, various commercially-available clocks are compared based on timing performance and cost. The sample figure below characterizes the oscillator phase drift of an Ultra-Stable Oscillator (USO), Chip-Scale Atomic Clock (CSAC), and Rubidium Atomic Frequency Standard (RAFS).



Time Transfer: Given that oscillator drift is representable as a linear system as defined in the above section, a linear Kalman filter is constructed – utilizing weak GNSS pseudorange and pseudorange-rate residuals as measurements – to track the oscillator state and provide corrections to align spacecraft time with GPS Time or Coordinated Universal Time (UTC) as desired. In such an architecture, onboard navigation systems are used to compute an estimate of range and range-rate with respect to visible GNSS satellites. These computed estimates can then be differenced against the measured, which reflects the oscillator phase and frequency offset – clouded by noise from errors in the signal generation to reception pipeline. This noise is well characterized by GPS and other GNSS specifications [6] for use on Earth, but can be factored into the filter with concessions for atmospheric propagation delays. This work covers filter specifics, including the construction process and measurement noise covariance matrices.

Results: Simulation results are provided for a variety of cases to demonstrate a sensitivity analysis of noise parameters, measurement frequency, and model accuracy. Below is a representative plot of clock bias from UTC as tracked by the Kalman filter given reasonable uncertainty in model accuracy, measurement quality, and clock calibration. Simulations were based on a Microsemi Space CSAC.



The above conditions result in a median 3σ clock bias error of 7.13 meters, or 23.8 nanoseconds. Various clock choices, measurement frequencies, and uncertainty levels are traded to determine reasonable configuations for different use cases. Design of experiments to test this system on hardware is also explored. This research demonstrates initial feasibility of GPS time transfer for accurate timekeeping at lunar distances.

References: [1] Babu N. (2022) *NASA Tech. Reports Server*, 20220013528. [2] Giordano P. et al. (2022) *ION ITM 2022*, 632-642. [3] Bhamidipati S. et al. (2022) *ION GNSS+ 2022*, 537-553. [4] Zucca C. and Tavella P. (2005) *IEEE UFFC*, 289-296. [5] Carpenter R. and Lee T. (2008) *AAS/AIAA SFM*, AAS 08-109. [6] Moorefield F. et al. (2020) *GPS SPS Performance Spec.*, 5th edition.

Development of a Reusable Lunar Environment Electrical Connector, The Dust Tolerant Connector.

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The Honeybee Robotics, Dust Tolerant Connector (DTC), solves the problem of a reusable electrical connector, cable of enduring the rigors of the lunar environment. Lunar regolith is infamously abrasive and detrimental to mechanism. The passive technology utilized in the DTC can contain and clear away regolith from the electrical connectors, ensuring a repeatable and reliable electrical connection for transferring power and data. Presented here is the design and development of a flight capable DTC configuration which was tested under relevant lunar vacuum, thermal, and regolith environmental conditions. Discussed are the challenges addressed by the DTC to enable astronaut or autonomous robotic interactions to reuse an electrical connection in the lunar environment. Also addressed are applications and challenges for implementation with various ISRU solutions and the needs for standardization of electrical interfaces.

Figure 1. TRL 6 DTC undergoring dirty TVAC testing

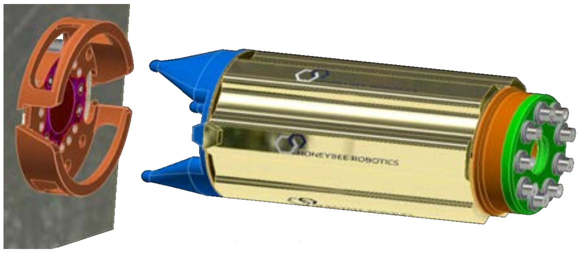


Figure 2. Next generation DTC with improved mechanism packaging

References: [1] J. Herman et al. (2011) Aerospace Conference [2] Kris Zacny, *Moon*, pp.235, 2012. [3] Jason Herman et al., "Dust-Tolerant Connector Development for Lunar Surface Systems", *2009 AIAA Space Conference Proceedings*, September 14–17, 2009. [4] S. Sadick, J. herman, D. Roberts. (2010). Dust-tolerant Electrical Connector (US8011941B2)

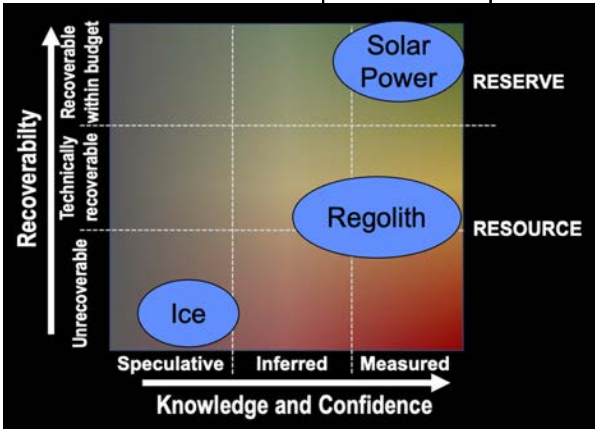
Classifying Lunar Resources: Adapting Terrestrial Standards. L. P. Keszthelyi[1], J. A. Coyan[2], K. A. Bennett[1], T.S. Gabriel[1], and L. R. Ostrach[1]. [1]U.S. Geological Survey, Astrogeology Science Center, [2]U.S. Geological Survey, Geology Minerals and Geophysics Science Center. (Contact: laz@usgs.gov)

Introduction: Lunar resources (i.e., natural substances that can be converted into useful commodities) are an exciting and growing topic for investigation with input needed from experts across many fields and nations. In such a setting, it is useful to have clear and standardized terminology.

The USGS has recently proposed a lunar resource classification scheme to meet this need [1]. This scheme attempted to balance multiple competing priorities. Although we strongly desired to maintain commonality with schemes used in terrestrial economic geology, no single classification scheme applies to all types of resources on Earth. Therefore, we selected concepts and terms that were widely used internationally for mineral and energy resources [2-5]. Further effort was made to choose terms compatible with lunar science, aerospace engineering, and common English.

Proposed Classification: Following the most widely used schemes on Earth, the classification has two axes (Fig. 1). The first reflects the level of knowledge one has on the characteristics of the resource. The second indicates the maturity and appropriateness of technologies to convert the resource into a commodity.

Figure 1. Proposed classification scheme for lunar resources with some example resources plotted.



Knowledge and Confidence. We propose three terms to describe the information available about a resource. "Speculative" means that theoretical and indirect reasons exist to expect deposits of the resource within the area of interest. Remote sensing data indicating the presence of a mineral without groundtruth observations would fit this category (e.g., polar ice). "Inferred" means that the properties of the deposit are estimated by extrapolating from other well-studied, geologically similar regions. An example would be regional types of lunar regolith. Finally, "measured" means the properties of the deposit have been directly measured across the area of interest. These *in-situ* measurements should be of sufficient quality and quantity to describe not just the typical values of key parameters but also their variability. Solar power is an example of a measured lunar resource.

Recoverability. We propose three categories to describe the match between in-situ resource utilization (ISRU) technology and the deposits. "Unrecoverable" means it is unlikely that a commodity will be economically obtained from the Moon in the next 30 years. This could be due to the low technical readiness level (TRL) of the ISRU technology, the poor quality of the deposits, or the lack of demand for what can be made from the deposits. ^{3}He might be put in this category given the maturity of fusion power plants. "Technically recoverable" means a commodity can be expected to be created from the deposit within the next 30 years. An ISRU capability that is approaching NASA TRL level 7, such as generating oxygen from bulk regolith, would fit this category. "Reserve" is restricted to deposits that can "economically" produce commodities useful for a commercial or exploration mission in the next 30 years. What is considered economical depends on the specifics of the mission (e.g., the mass, power, cost, and risk budgets). The use of solar energy to produce electrical power fits this category for many lunar missions.

Conclusion: We feel the proposed classification scheme has many merits, combining simplicity and utility. We are presenting at the Lunar Surface Innovation Consortium to solicit suggestions for its improvement and work towards a consensus to adopt it within the lunar community.

References: [1] Keszthelyi L. P. et al. (2023) USGS Circular 1507. [2] U.S. Bureau of Mines and U.S. Geological Survey (1980) USGS Circular 831. [3] Society of Petroleum Engineering (2018), https://www.spe.org/en/industry/petroleum-reources-management-system-2018. [4] UN Economic Commission for Europe (2019) ECE Energy Series, 61. [5] Schmoker, J.W., and Klett, T.R., (2005) USGS Digital Data Series DSS-69-D.

The importance of particle morphology in understanding lunar regolith.

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Knowledge of the mechanical behavior of lunar soils is crucial for successful lunar missions. This study investigates the potential impact of particle shape and size on the geotechnical properties and soil-structural interaction of lunar simulants. Despite numerous studies on lunar regolith, most have utilized artificial simulants that do not accurately represent the grain morphology of lunar soils.

Particle shape plays a significant role in determining the behavior of soils, influencing factors such as stiffness, strength (1), interface friction, and abrasion characteristics (2). However, the lack of consideration for realistic particle morphologies in lunar simulants can lead to inaccuracies in our knowledge of lunar regolith behavior. This knowledge gap poses risks to future lunar exploration missions and potential habitat construction.

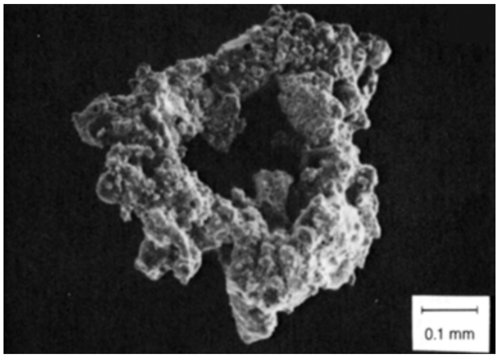

Figure 1 Lunar regolith particle with rough torus shape (3)

Addressing the discrepancy between lunar regolith and simulants is essential for advancing lunar geotechnical engineering. By incorporating realistic particle morphologies into lunar simulants, we can improve the accuracy of laboratory experiments (in an element and model scale) and simulations, e.g., Discrete Element Method (DEM) studies, etc. This will enable researchers to predict the mechanical behavior of lunar soils with the environmental conditions of the moon's surface and mitigate potential risks associated with lunar regolith engineering.

Moreover, a deeper understanding of particle morphology in lunar simulants could facilitate the production of more realistic materials for lunar surface testing. These advancements have the potential to enhance the safety and success of future lunar missions, reducing uncertainties and optimizing engineering designs for lunar habitats and infrastructure.

In conclusion, recognizing the significance of particle shape in lunar soil mechanics is crucial for advancing lunar exploration and development efforts. In the current study, we present our research to advance our knowledge regarding the shapes and sizes of the individual particles that make up the lunar regolith which has a significant influence on soil fabric, and in turn, influences the strength and stiffness of the regolith. Understanding how these parameters influence the mechanical behavior of lunar soils is vital for the success of future lunar missions and the establishment of sustainable lunar habitats. Through comprehensive analysis and experimentation, we aim to contribute to the development of more accurate lunar simulants and engineering models, ultimately reducing risks associated with lunar regolith engineering and advancing human exploration to the moon and beyond.

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Carbonnanotube-reinforced lunar simulant-based geopolymers: Curing regimes.

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Introduction: The research aims to find a suitable construction material using In-Situ Resource Utilization (ISRU). The material will be based on lunar regolith, which will act as a binder in an in-situ building material called geopolymer concrete. Geopolymer concrete usually requires a binder and aggregates, along with activators, which are aqueous alkaline solutions.

NASA's Artemis mission aims to establish long-term human and robot presence on the Moon, which is why it's essential to develop infrastructure materials that can withstand the harsh lunar environment.

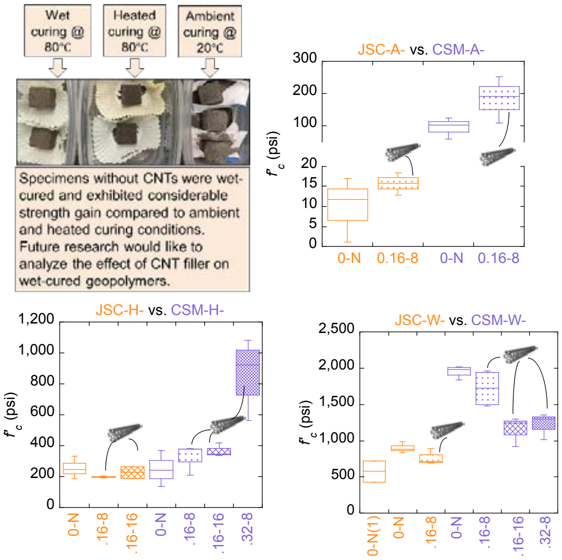
Carbon nanotubes (CNTs) are rolled-up sheets of graphene that have been shown to improve mechanical properties when used as reinforcement fillers at certain mix design ratios in Portland cement research. They are lightweight and are typically used in small quantities in mix designs, which makes them reasonable for spaceflight cargo.

Research Objectives: The research questions are to answer how carbon nanotubes affect the compressive strength of lunar simulant-based geopolymers (geopolymerization), and how they affect the water retention of geopolymers.

Experimental Program: Two lunar simulants were used - JSC-1A representing the Mare region and CSM-LHT-1 representing the Highlands region. We considered two different concentrations: 0.16% and 0.32% of the weight of the cement-grade binder. We identified 30% of the precursor material as the cement-grade binder, and accordingly, CNT proportions of 0.04% and 0.08% were used for the entire mix design. It is worth noting that the mixture design was consistent across both JSC-1A and CSM-LHT-1, ensuring a standardized approach across different lunar simulants.

All specimens were subjected to different water availability and three curing methods. Three curing regimes include as follows: Ambient condition (denoted as -A): After demolding, the sample was stored in an environment with a temperature of 23.6 ± 1.2 °C and a relative humidity of 55-60%. Two oven curing regimes are denoted as H and W: After demolding, the sample was stored in an oven with a temperature of 80°C. One sample was covered with a lid to prevent the evaporation of water vapors, while the other was left open. This was done to limit the amount of water moisture that comes into contact with the sample.

Findings: In all the groups of conventional curing regimes, CSM-LHT-1 outperformed JSC-1A groups regardless of the presence of CNTs ((purple versus orange in Fig. 1).



Specimens without CNTs were wet-cured and exhibited considerable strength gain compared to ambient and heated curing conditions. Future research would like to analyze the effect of CNT filler on wet-cured geopolymers.

Figure 1 CNT effects in each curing regime: Test samples (Top left); A series (Top right); H series (Bottom left); W series (Bottom right)

The benefits of CNTs can be more pronounced when the curing temperature is ambient. When exposed to the curing temperature of 80 °C, the correlation of CNTs and simulant types is complex. It requires further study. For example, the extended sonication time (16 minutes) or higher CNT contents (0.32%) are more positive in the curing regime of H (open lids). However, the W regime (closed lids) led to opposite trends, exhibiting that the extended sonication (16 minutes) and higher concentration of CNTs (0.32%) led to a reduction in strength. Generally, CNTs positive impact on strength gain was observed in the test program.

Acknolegements:

The material is based upon work supported by the NASA National Space Grant College and Fellowship Program and the Kentucky Space Grant Consortium under NASA award number 80NSSC20M0047.

Design Study of Surface to Surface Laser Power Beaming on the Moon. G.A. Landis[1], S.R. Oleson[1], and the Compass engineering team, [1]NASA Glenn Research Center, 2100 Brookpark Road, Cleveland OH. Contact: geoffrey.landis@nasa.gov

Introduction: Using a laser to send power to a photovoltaic receiver has been proposed to transmit electrical power on the moon, particularly for applications such as powering a rover in near-polar permanently-shadowed regions (PSR) where solar power is not available[1,2].

In this work, we did an engineering design study of a near-term laser surface-to-surface power beaming using the VSAT as the laser platform.

Study: To maximize the distance of beaming, taking into account possible surface irregularities and the short distance to the horizon of the moon, it is desirable to emplace the laser at an elevation above the surface. The Vertical Solar Array Technology (VSAT)[3] is a NASA program developing a solar array mounted vertically on a 10-m tall mast, designed for emplacement on a Commercial Lunar Payload Services (CLPS) lander to provide 10-kW (BOL) power near the south polar region of the moon, with a target readiness date of 2028. We used this design as the starting platform and the power source for a laser power beaming station. By mounting the laser beam director at the top of the solar array mast, a viewing distance to power receivers up to 10 km is possible.

Requirements for the system were to be able to provide 300 W of continuous usable power to users including CLPS landers, VIPER[4] class rovers, or the proposed Lunar Terrain Vehicle. The requirement was to able to transmit power to a distance of up to 10 km, over a design lifetime of 5 years, and fitting within a total system landed mass under 625 kg.

Design: Figure 1 shows the beaming station mounted on the top of a VSAT array on a conceptual CLPS lander. A commercially-available high-power 1.07-μ diode-pumped fiber laser is mounted on the deck of the lander, with laser output sent to the laser beam director by a fiber-optic cable. A 7 square meter deployable radiator keeps the laser within operating temperature limits. The beam director, based on the design of a prototype unit developed by the University of California Santa Barbara[2], is shown in green at the top of the mast. The system is powered by the 7-kW VSAT array.

Concept of Operations: The system beams power for 57% of the time, with 44% of the time idle (accounting for the time when the VSAT array is itself in shadow). 1595 Watts of optical power are output in the beam. Accounting for receiver efficiency and beam losses, this results in an output onto the 1.5-meter receiving photovoltaic array of 542 watts. Of this, 300 watts is directly available to the user, while 242 watts is directed to the batteries for use while the beam is not available.

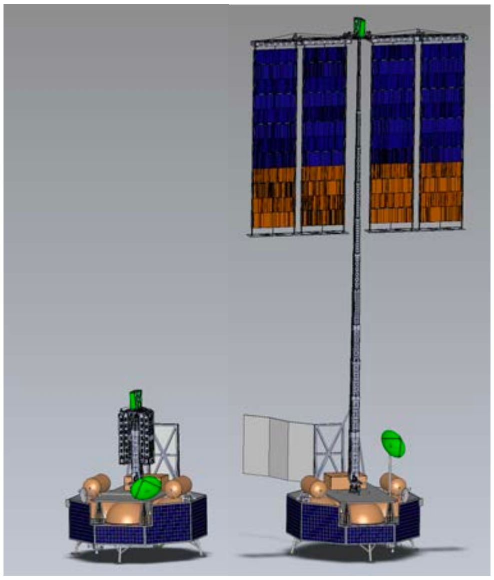


Figure 1: Beaming station stowed (left) and after deployment of the thermal radiator and VSAT array and 10-m mast (right). (note that the bottom third of the array area is populated by dummy panels rather that solar cells, part of a technology demonstration[3] to show capability of deploying a larger array.)

Conclusion: An engineering design and concept of operations was done for beaming laser power from a small lander to users (landers or rovers) within a 10-km distance.

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LTVS as an Enabler for the Endurance-A Mission. M. C. Six[1], K. A. Stolleis[1], A. G. Lillard[1], D. A. Swan[1], [1]Lockheed Martin Space, 12257 S Wadsworth Blvd, Littleton, CO 80127. (Contact: melissa.six@lmco.com)

Introduction: In 2022, the NASA Planetary Exploration Decadal Survey identified the Endurance-A lunar exploration and sample collection mission as its number one priority mission for NASA's Lunar Discovery and Exploration Program [1]. Lockheed Martin (LM) is studying the feasibility of using the NASA Lunar Terrain Vehicle (LTV) [2] as a platform to conduct the Endurance-A mission rather than constructing a bespoke rover for the mission. Through analysis of LTV requirements and overlap with the Endurance-A goals [3], the traverse can be performed faster and at lower cost and risk while still completing or exceeding all the science goals of Endurance-A. As part of the feasibility study, LM examined multiple alternate traverse paths to allow LTV to complete Endurance-A, all while maintaining availability for Artemis crewed mission support. LTV has multiple advantages in comparison to the proposed Endurance rover that can be leveraged in performing the alternate traverses including additional sensing for both science and autonomous operations, higher operational speeds while driving, and increased payload capacity for carrying samples. LTV has a nominal launch of late 2028, which also accelerates the nominal timeline of Endurance-A and can provide additional opportunities to expand the science mission in and around the lunar South Pole and Aiken Crater region.

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[3] J.T. Keane, S.M. Tikoo, and J. Elliott, (2023) *Endurance: Lunar South Pole-Aitken Basin Traverse and Sample Return Rover*

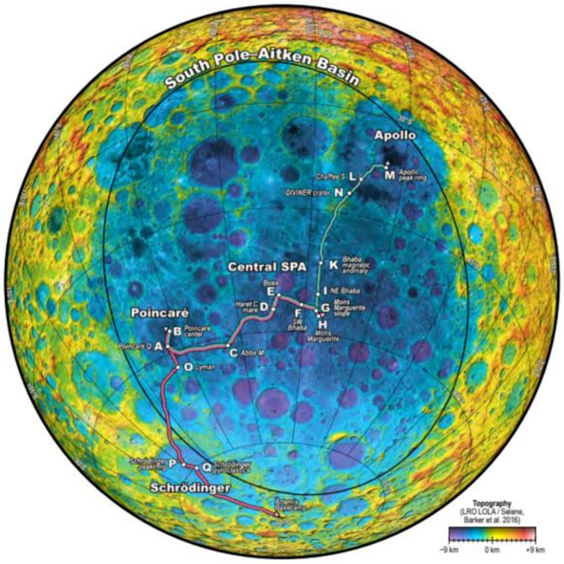

Figure 1 – Endurance-A and Endurance-R Traverses [3]

Analysis of the Efficiency of Percussive Excavation: Implications for CONOPS and Hardware Development.

J. M. Long-Fox[1], R. P. Mueller[2], K. A. Zacny[3], and D. T. Britt[1], [1]University of Central Florida Department of Physics, 4111 Libra Drive Room 430, Orlando, FL, 32816, [2]NASA Kennedy Space Center Swamp Works, Merritt Island, FL 32593, [3]Honeybee Robotics, 2408 Lincoln Ave, Altadena, CA 91001. (Contact: jared.long-fox@ucf.edu)

Introduction: Efficient excavation for lunar resource acquisition and infrastructure development in the low gravity (1/6 g) environment requires force reduction techniques such as percussion to enable equipment to maintain traction and lower required force outputs. This study investigates the efficiency of percussive excavation as compared to static excavation. The results of this research are intended to inform requirements for lunar excavation equipment and modeling/planning efforts.

Methods: The data used in this study [1,2] are results from a replica Surveyor III SMSS scoop in a series of percussive excavation experiments that varied frequency, simulant (JSC-1A) density, and scooping depth. To evaluate the relative cost (power draw of the percussion motor) of excavation as a function of percussive frequency and scooping depth, experiments [1,2] using a range of percussive frequencies (0-1750 beats per minute, BPM) and scooping depths (30, 50, and 70 mm) with a speed of 5mm/s in high (>95%) relative density simulant are used here. Specifically, the ratio of motor power to total excavation force (W/N) and ratio of percent force reduction to percussion motor power (%/W) are calculated and fit with linear ($y = mx + b$) and exponential ($y = ae^{bx} + c$) functions, respectively.

Results: The two metrics of efficiency are plotted as a function of percussive frequency: excavation force per unit power (Figure 1) and percent force reduction per unit power (Figure 2).

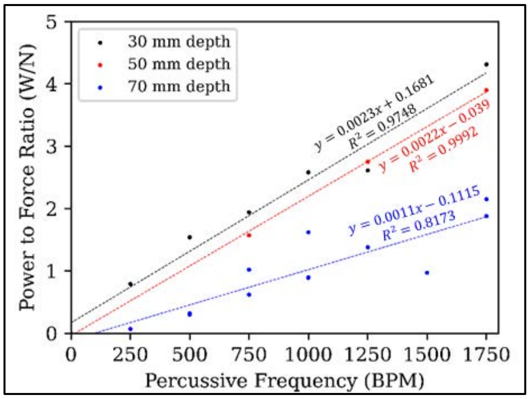

Figure 1. Percussive frequency vs power cost per total force during excavation.

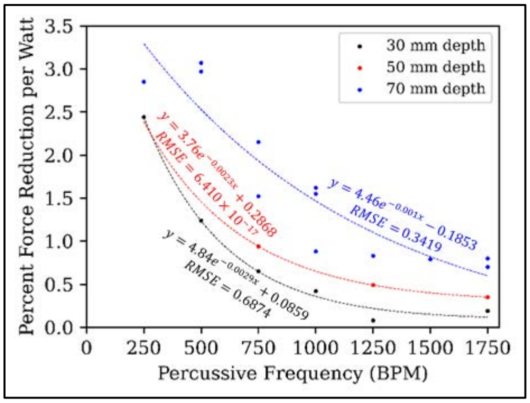

Figure 2. Percussive frequency vs percent force reduction (compared to static excavation) per unit power.

Discussion: The ideal excavation force reduction system is the one that takes the least amount of power to reduce the required force for excavation to acceptable levels. These analyses show that, for the system [1,2], the power cost per force of excavation is lower at low percussive frequencies, and that there are diminishing returns in force reduction with increasing percussive frequency (power draw). While the analysis here is specific to the experimental setup in [1,2], the general trends and considerations are expected to be true for any force-reduced excavation and hence can used in excavation hardware development and subsequent CONOPS for lunar excavation.

Conclusions: Excavation force reductions must be optimized to offer the most efficient excavations in terms of power costs and relative to hardware capabilities/requirements. Computational tools to aid in development of lunar excavation hardware and tool paths must be able to reliably predict excavation forces and power costs given specifics of force reduction techniques (e.g., power, frequency) and regolith properties.

Acknowledgements: This work is supported by a NASA Space Technology Graduate Research Opportunity (NSTGRO) Fellowship under NASA Cooperative Agreement 80NSSC23K1173.

References: [1] Green, A. (2011), Doctoral Dissertation. [2] Green et al. (2013), *J. Aero. Eng.* 27(1), 87-96.

RIDER: Ready to Roll. J. M. Long-Fox[1], M. P. Lucas[2], C. R. Neal[2], and D. T. Britt[1], [1]University of Central Florida Department of Physics, 4111 Libra Drive Room 430, Orlando, FL, 32816, [2]University of Notre Dame Department of Civil and Environmental Engineering and Earth Sciences, 156 Fitzpatrick Hall, Notre Dame, IN 46556 (Contact: jared.long-fox@ucf.edu)

Introduction: Safe and efficient rover mobility is crucial for long-term, large-scale human and robotic presence on the Moon and other planetary bodies. However, lunar and planetary regolith is notoriously difficult to operate in, a problem exacerbated by the extreme environments on extraterrestrial surfaces (fine dust, low gravity, thin/no atmosphere). To ensure reliable mobility systems during planetary surface operations, proper laboratory testing must be performed to optimize wheel-regolith interactions (terramechanics) and understand operational limits of a particular rover in particular regolith and regolith conditions (density, stratigraphy, composition, etc.). RIDER (Figure 1) [1], a novel, full-scale rover wheel testing facility that has been developed and made available to the planetary science and engineering community.

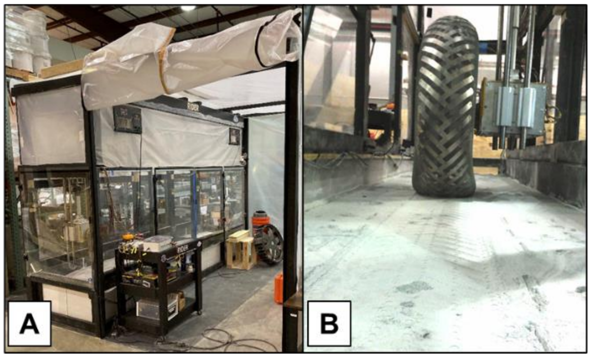

Figure 1. (A) The RIDER terramechanics testbed, including dust mitigation/containment features (sealed doors, airlock, air filters) and control station. **(B)** Replica Lunar Roving Vehicle (LRV) wheel being tested in RIDER as part of [2].

RIDER Systems and Capabilities: The RIDER test facility is designed and built to simulate planetary rover wheel-regolith interactions and hence accounts for rover characteristics (weight, wheel design, speed, torque) and planetary regolith properties (well-characterized, high-fidelity simulants, compaction/density profiles). Specifically, RIDER subsystems (some shown in Figure 2) include an enclosed regolith simulant bin, simulant compaction equipment, power, signal/control, and data logging system, a load application system, wheel drive and mounting systems, rails and gantry, environmental monitoring and control, dust mitigation, illumination, and video recording systems. RIDER has successfully completed the GATOR [2] test campaign, demonstrating the ability to perform intensive test campaigns with a variety of wheel designs.

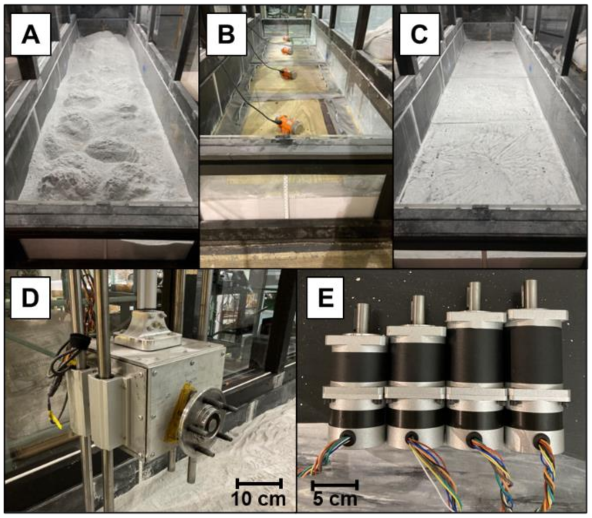

Figure 2. (A) uncompacted LHS-1E in RIDER simulant bin, **(B)** compaction equipment in use, **(C)** highly compacted simulant, **(D)** motor box and linear bearings and rails, **(E)** interchangeable RIDER motors with different gear reductions.

RIDER Resources and Science Team: RIDER is housed at Exolith Lab at the University of Central Florida (UCF) so RIDER users have easy access to bulk quantities of lunar, martian, and asteroid regolith simulants that can be customized as necessary to meet testing needs. The RIDER Science Team (the authors of this abstract) are available to aid RIDER customers with experiment designs, simulant selection, and cater data collection and analysis to the particular test campaign.

Acknowledgements: RIDER was developed by UCF and the University of Notre Dame (UND) under the NASA Solar System Research Virtual Institute (SSERVI) Center for Lunar and Asteroid Surface Science (CLASS) through NASA Cooperative Agreement 80NSSC19M0214.

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Property Prediction Model for Molten Lunar Regolith.

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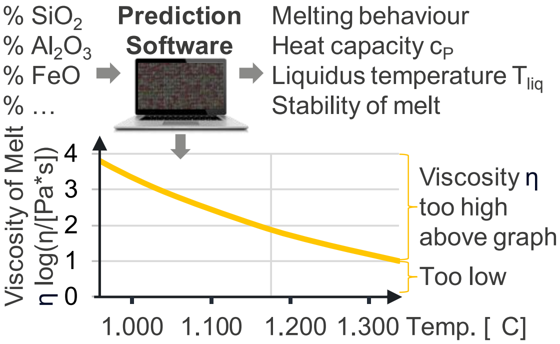
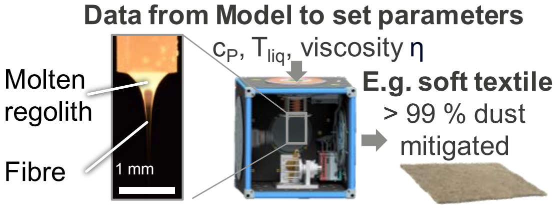
Introduction: With over 250 planned activities in the next decade, the Moon is increasingly becoming a focus of research and industry. Leading space agencies prioritize the use and processing of raw materials (ISRU) on the Moon due to its potential to save $1.5 million per kilogram by eliminating transportation costs from Earth. Utilizing Lunar regolith by melting it is the most cost-effective and robust ISRU method. Maintaining a consistent chemical composition is crucial for the physical behaviour of molten Lunar regolith. Therefore, it is important to ensure homogeneity in the chemical composition. Even slight changes of ≥ 0.5 wt.-% can render the regolith melt unstable and unusable for further processing, significantly affecting its melting properties. Accurate prediction of melting properties is imperative for all ISRU technologies that involve melting or re-melting regolith.



Melt Property Prediction: Prediction of melt properties: To address this deficiency, a prediction software model has been developed as shown in the following figure. The input to the model is the oxide composition of the regolith. Predicted variables include melting behaviour, heat capacity, fluid temperature, stability, and viscosity behaviour.

Validation based on MoonFibre: The reliability of the model was validated by spinning tests using MoonFibre. LHS-1 simulants were first determined using the model. This was used to define the settings for melting the simulants. For example, it was determined that the processing temperature of the molten regolith, shown in the figure below, would allow fibre formation. Fibres with a diameter of 15 µm were successfully produced from the melted simulants. The fibres have a tensile strength of 1.3 GPa, 26 times greater than sintered or 3D printed materials. In addition, the surface area is 100 times greater than that of monoliths. Textiles made from MoonFibres are therefore suitable for hydroponic systems, but also for landing sites, as Lunar dust is reduced by > 99 %.



The spinning tests were then repeated in a research rocket at 0 g and the model data was again validated. MoonFibres were generated and it was shown that the spinning process is robust enough for a rocket launch and that the model is reliable.

Scalability of Model for Moon and Earth: In summary, it is essential for all ISRU technologies to have a reliable prediction of the melting properties of the regolith. The model used is therefore also required for sintering and additive manufacturing technologies. High strength fibre reinforced sintered materials or other composites can be produced. In addition, the model is already being used on land to predict the melting behaviour of basalts for fibre production.

Acknowledgment: MoonFibre is funded by German Aerospace Center DLR and European Space Agency ESA BIC North-Rhine-Westphalia, Germany.

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Implementing Biological ISRU for Sustainable Off-World Food Production.

K.L. Lynch[1], R. L. Loureiro[2], A.C. Simpson[3], D. A.G. Palmer[4], L. E. Fackrell[5], [1]Lunar and Planetary Institute-USRA, 3600 Bay Area Blvd, Houston, TX 77062, [2]Winston Salem State University, [3]Blue Marble Institute of Space Science, [4]Florida Institute of Technology [5]Jet Propulsion Laboratory (Contact: klynch@lpi.usra.edu)

Introduction A critical component to long-duration deep space exploration, including both Moon and Mars habitation, is developing self-sustainable food production and life support capability (e.g., bioregenerative life support). A key recommendation from the 2011 National Research Council Decadal Survey on Biological and Physical Sciences in Space, further bolstered by 2018 Midterm Assessment of Implementation of the 2011 Decadal Survey, states that "***NASA should develop a research program aimed at demonstrating the roles of microbial-plant systems in long-term life support systems***". To accomplish this, it will be necessary to understand how to optimally integrate plant-microbe systems with planetary in-situ resources long-term (e.g. Biological ISRU or BISRU) as capitalization of in situ planetary resources will be necessary to fully develop and sustain long-term, Bioregenerative Life Support Systems (BLSS) [1-4]. Further, it will be critical to identify, develop and optimize the technical systems and processes for operating and maintaining BISRU systems at scale to provide sustainable resources to a human habitat population. This will require coordinated interdisciplinary communication and partnership between plant biologists, microbial ecologists, molecular biologists, engineers, and planetary scientists. As such, several research projects are underway to address low-level process & technology knowledge gaps for implementing BISRU systems. Here we will present an overview of two such projects that are working to start addressing early science and technology knowledge gaps for BISRU-based food production: CHRGE and Plant Trek.

CHRGE: The Comparing Hydroponics and Regolith Growth and Evolution Study (CHRGE) evaluates the similarities and differences between the two distinct methods for producing off-world food crops: hydroponics and regolith-based agriculture (RBA). Each method presents its own challenges. Fluid- based hydroponics requires significant water resources while also risking fungal and bacterial contamination. Lunar (and martian) regolith, on the other hand, is void of significant organics and often lacks key nutrients (e.g. nitrogen) found in Earth soil. To date, no direct comparisons between hydroponic and regolith-based systems have been conducted for space applications, though an understanding of these differences is crucial for successful off-world infrastructure planning and success. The purpose of CHRGE is to address this knowledge gap by directly comparing the inputs and outputs between hydroponic and RBA systems for a variety of crops to understand how to best integrate these types of systems into long-term human habitation.

Plant Trek: Plant Trek addresses the challenge of developing agriculturally stable and usable soil from lunar and martian regolith simulants, enabling plant growth, sustaining plant-microbiome interactions, minimizing plant stress, and optimizing food production and life support by using approaches based on primary succession in Earth ecosystems. Plant Trek evaluates bioremediation of toxic elements in regolith such as perchlorate by identifying and testing critical microbial consortia involved in relevant metabolic pathways and evaluating microbial community evolution, nutrient availability, and soil structure development. Understanding these metrics can both reduce human health risks and optimize carbon and nitrogen content, nutrient availability, and soil structure, improving drainage and facilitating plant growth. The goal of Plant Trek is to provide an integrated process pathway for soil formation using in situ resources (regolith), thus facilitating the development of sustainable agricultural substrates on the Moon (and eventually Mars).

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Passive Deployable Radiator Covers Utilizing Shape-Memory Alloys for Increased Lunar Night Operation. **A. S. Kaplan, W. L. Adams, J. A. Marlin, and W. J. Coogan, Firefly Aerospace, Inc. (5900 Highway 183A Leander, TX 78641; alex.kaplan@fireflyspace.com).**

Introduction: A fundamental challenge of long-duration lunar surface operations is surviving both the intense heat of lunar day, and frigid cold of lunar night. The radiator area required for heat rejection during hot periods results in heat losses during cold periods. Compensating for these heat losses with electric heaters alone levies high power requirements on the vehicle, which are especially difficult to maintain in the two-week absence of sunlight on a battery and photovoltaic spacecraft. These conflicting requirements are more efficiently reconciled using devices like thermal switches and louvers to dynamically tune heat flows. Such components operate passively, reducing demands on operators, control systems, and power systems, and control heat flow as suited to the environment. Thermal switches mechanically connect or disconnect a conductive path to control heat losses, while louvers are hinged flaps, like window blinds, with a heat rejection ratio of up to 20 [1]. Louvers often use bimetallic springs, leveraging the varying CTEs of two different metals to rotate an insulating cover and expose the radiating surface below the louver [2]. Driven by mass constraints of lander missions, we describe here a variation on the classic louver that achieves similar performance with less mass using commercially available components.

Designing with Nitinol: Firefly engineers have developed a novel approach to controlling thermal losses by using shape-memory alloy springs instead of bimetallic springs for thermal mechanisms. Shape-memory alloys return to an original “trained” shape when exposed to heat, even after being deformed. Nitinol, a nickel and titanium alloy, is trained to the desired shape by heating the metal to 500° C and then quenching [3]. The material has distinctly different and repeatable properties around a given set temperature, oscillating between the trained shape and a highly flexible one. The two states passively rotate a cover both on and off a radiator.

Passive Radiator Covers: To create a deployable cover, we used an opposing series of nitinol springs and constant force springs. On the free edge of the radiator, we installed a hinge supporting a Multi-Layer Insulation (MLI) cover. A lever on the hinge supports both sets of springs, which mount to the radiator. The figure shows both sets of springs attached to the radiator cover lever. The constant force springs and nitinol springs apply opposing forces which actuate the MLI cover to separate positions for the hot and cold cases. When the temperature reaches a desired setpoint, the nitinol springs return to their “trained” position, overcoming the force of the constant force springs and raising the MLI flap off the panel. If the temperature drops below the setpoint, the nitinol becomes compliant and the constant force springs overcome the force of the nitinol springs, returning the flap to its position covering and insulating the radiator. The mass savings of this approach come from reduced number of moving parts compared to a conventional louver design. Additionally, unlike a conventional louver, the radiator is covered and uncovered by a large single flap, and the flap can rotate up to 130 degrees from the radiator, ensuring maximum view factor to deep space.

Summary: Passive components provide thermal control with a simple concept of operations and no power or commanding demands. By combining constant force springs with springs made of a shape-memory alloy like nitinol, Firefly created a simple, lightweight, and easy-to-manufacture passive deployable radiator cover that offers a higher view factor in the deployed state than a conventional louver. Components like this will be key to sustain humanity’s presence on the Moon through the extremes of lunar day and night.

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Moon Construction: Estimating Time and Cost for Extreme Conditions. P. Martin[1,2], H. Nguyen Ph.D.[2,3], V. V. Singh[2,3], C. Moore[2,4], A. Zavichi Ph.D.[2,5], F. Callison[2,6], B. Hyatt Ph.D.[2,7], R. Peterson[2,8], D. Seifert[2,9], J. Reginato Ph.D. [2,10], M. Linton Ph.D.[2], [1]University California, Davis, 1 Shields Ave, Davis CA 95616, [2]Institute for Construction Innovation Thought Consortium (i4Ci), [3]University of California Berkeley, 762 Davis Hall, UC Berkely, Berkeley, CA 94720, [4]University of Utah, [5]Port of Los Angeles, [6]Rudolph & Sletten, Inc., [7]California State University, Fresno, [8]U.S. Department of State Bureau of Overseas Building Operations, [9]State of California Department of Transportation (CalTrans), [10]Swinerton Builders Inc., (Contact: pmartin@i4ci.org)

This presentation explores the challenges of accurately predicting costs and timelines for projects in extreme environments, mainly emphasizing building a permanent human habitat on the Moon. This team proposes a holistic framework that combines objective and subjective predictive analysis with production model sequences, aiming to provide a more reliable approach to mitigate the uncertainties inherent in extreme conditions. We will further strengthen this framework by drawing insights from case studies of Earth-based projects in similarly challenging environments like Antarctica.

Objective and Subjective Predictive Analyses (OSPA) form the core of our approach. Objective analysis involves leveraging historical data, industry benchmarks, digital models, and quantitative modeling techniques such as Monte Carlo simulations to establish a robust foundation. On the other hand, subjective analysis incorporates expert opinions, risk assessments, and scenario planning to address the human element and unforeseen circumstances, ensuring flexibility and adaptability throughout the project lifecycle.

In this presentation, we will address:

- Comparing extreme conditions projects, here on Earth and in contrast to Moon Construction. What considerations are critical for cost reliability?
- What technologies are being used to help predict causality and its effect on the estimate contrasting to actual reality when constructing on the Moon.
- We will discuss the major role that robotics and automation play in integrated cost prediction and control construction projects
- We will explore new techniques being developed for interactive simulated cost and production modeling.
- Examine how means and methods of construction have an exponential impact and must be considered appropriately during the estimate.
- Explore major risks exposed by Moon dust.

Implementing lunar construction projects is a monumental task, requiring innovative project management approaches. Our proposed framework, informed by insights from Earth-based case studies and blending objective and subjective analyses, provides an avenue for achieving reliable cost and time estimations for lunar endeavors and other large-scale and extreme projects.

Advancement of tire and visual perception technologies for the Lunar FLEX rover.

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Introduction: Venturi Astrolab, Inc. (Astrolab) is developing Lunar FLEX, a semi-autonomous, remotely operable lunar rover. FLEX offers unique commercial potential due to its novel mobility system and modular payload architecture, while also carrying two suited astronauts and their equipment (Figure 1). Astrolab has developed a full-scale, terrestrial proof-of-concept FLEX rover that has successfully carried out activities and operational scenarios that will be required on the lunar surface [1].

Figure 1: Lunar FLEX's modular payload interface and novel mobility system enables crew transport, robotic science, logistics, and infrastructure deployment

Commercial mission: Astrolab announced in March 2023 that it had signed a launch service agreement with SpaceX to send an uncrewed version of FLEX to the lunar south polar region as soon as 2026 on a Starship Launch & Landing System. Astrolab has signed at least eight customer reservation agreements for this mission, whose payloads include technology demonstration of in-situ water extraction and infrastructure construction, experiments in plant growth and lunar sustainability, and a DNA seed bank.

Technology maturation: In preparation for its upcoming lunar mission, Astrolab has advanced the maturity of two key FLEX subsystems through simulation and testing campaigns.

Mobility and tires. The Venturi Tires used on FLEX have been developed in collaboration with Venturi Lab. They employ a sacrificial tread layer and a layered shear band to enable an extreme 26° slope capability, -250°C to +125°C temperature limits, and 1300 km/year range. Under its 2022 NASA Announcement of Collaboration Opportunity (ACO) award, Astrolab is conducting two development test campaigns with NASA, each covering launch vibration, extended lunar night survival (extended cold and vacuum), traction performance, and operational life (Figure 2).

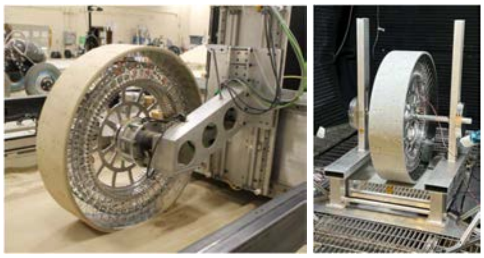

Figure 2: Traction (left) and night survival (right) tests of the Venturi Tire as part of its first development testing campaign under the NASA ACO award

Visual perception. FLEX provides structured and unstructured illumination to perform vision-based hazard perception in the challenging low-angle solar lighting present at the lunar south pole. Astrolab has incorporated an Apollo-correlated bidirectional reflectance model of lunar regolith [2] into an optical and radiometry simulation software package to optimize the vision system design parameters for this environment. Additionally, a new onsite lunar scene simulation lab allows the vision system to be tested in lunar-representative lighting and has been used to successfully demonstrate stereo depth map reconstruction in partially shadowed scenes using structured dot projection (Figure 3).

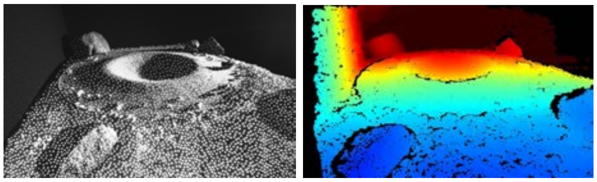

Figure 3: Lab-constructed partially shadowed lunar scene illuminated by a pseudorandom dot projector (left) and the depth map constructed with active stereo (right)

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Environmental Testing for the Cold Operable Lunar Deployable Arm (COLDArm) System. P. Glick[1], A. Brinkman[1], D. Newill-Smith[1], R. Dillon[1], A. Umali[1], K. Carpenter[1], R. McCormick[1], N. Jimenez[2], L. Fradet[3], G. Levanas[3], R. Fleischner[3], [1]Jet Propulsion Laboratory, California Institute of Technology, 4800 Oak Grove Dr. Pasadena, CA 91109, [2]NASA Glenn Research Center, 21000 Brookpark Rd, Cleveland, OH 44135, [3]Motiv Space Systems, Inc, 350 N Halstead St., Pasadena, CA 91107 (Contact: Ryan.L.McCormick@jpl.nasa.gov)

Introduction: The Cold Operable Lunar Deployable Arm (COLDArm) will enable robotic manipulator operations without heaters on the lunar surface in cryogenic conditions. This could include during the lunar night or in permanent shadowed regions (PSRs). Additionally, eliminating mechanism heaters can help preserve volatile sample integrity during collection. The COLDArm engineering model has previously performed a ground demonstration in lunar regolith simulant of geotechnical property experiments consistent with a potential lunar surface technology demonstration [1]. The team recently completed environmental testing to achieve technology readiness level (TRL) 6. The dust seal testing, system vibration testing, and system thermal vacuum (TVAC) demonstration are detailed below.

Dust Seal Testing: Actuator dust seal testing was completed at Glenn Research Center (GRC) consistent with NASA-STD-1008. Expected actuator revolutions were modelled for potential COLDArm and Endurance mission concepts. Size fraction sorted JSC-1A simulant was used due to the material's high glass and lithic content, highly abrasive qualities, and availability at GRC. An actuator was placed in the GRC Dust Deposition System. Testing was consistent with 12x life for a potential lunar tech demonstration and 1x life for the Endurance mission concept. After the test, the actuator was disassembled to visually confirm the seals prevented simulant from entering the actuator internal mechanism.

System Vibration Testing: Vibration testing was completed on the COLDArm system based on the General Environmental Verification Standard (GEVS). The testing exposed the system to the random vibration environment in each axis for a 2-minute duration. Accelerometer responses were compared before and after the test to confirm no structural damage occurred. Actuator range of motion tests were completed after the test to verify the system was operational.

System Thermal Vacuum Testing: The COLDArm system first completed a non-operational hot temperature bake-out exposure of greater than 100 C and below the GEVS vacuum pressure. The system then completed a TVAC test for operational hot and non-operational/operational cold, shown in Figure 1. At the hot operational temperature of approximately 60 C, the system demonstrated an unstow sequence from the launch lock and actuator motions. A weighted end effector replaced the scoop end effector to produce worst case joint torques anticipated on the lunar surface in a potential lunar technology demonstration. Both a liquid nitrogen heat exchanger and liquid nitrogen flooded shroud were utilized to reach cryogenic temperatures. At cryogenic system temperatures, the robotic joints were actuated with the motor controllers consistent with joint torques anticipated for a potential lunar technology demonstration.

Acknowledgements: The project is funded through the Lunar Surface Innovation Initiative (LSII) and managed by the NASA Space Technology Mission Directorate (STMD) Game Changing Development (GCD) program. The COLDArm system is developed with industrial partner, Motiv Space Systems, Inc (Pasadena, CA). Research described in this publication was carried out at the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration (NASA). U.S. Government sponsorship acknowledged.

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Figure 1: COLDArm system installation in 7 foot diameter thermal vacuum (TVAC) chamber at JPL

SAMPLR Mission Progress Report.

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Introduction: The Sample Acquisition, Morphology Filtering, and Probing of Lunar Regolith (SAMPLR) project is a five degree-of-freedom (5DOF) robotic arm that will study the properties of the lunar surface environment as well as demonstrate key planetary robotic technologies.

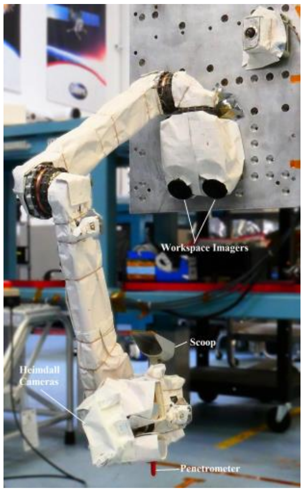

Figure 1: SAMPLR demonstrating a penetrometer plunge trajectory.

SAMPLR is equipped with a scoop-sieve, a regolith penetrometer, as well as workspace and microscopic imagers. Partners include the Colorado School of Mines (CSM) leading the regolith penetrometer study and the Planetary Science Institute leading the Heimdall imager hosted payloads. SAMPLR is manifested as part of NASA's Commercial Lunar Payload Services Program.

Background: The mission has the following primary objectives:

1. Demonstrate use of the arm on the lunar surface to qualify its mechanisms and topology for use in future missions at varied locations and for use with additional payloads (turret-mounted or unused mounting interface): *The modular design with integrated avionics, thermal management, and flight software enables tailoring to future needs such as excavation, deployments, and assembly.*

2. Capture regolith geotechnical data with a novel penetrometer design leveraging a cone probe proven in a simulated lunar environment (in cooperation with CSM) and a flight force-torque sensor (in production for DARPA RSGS and NASA OSAM-1): *A vertical plunge will provide data on the penetration and relaxation of the lunar regolith, valuable for in-situ excavation and prospecting for ice [3].*

3. Demonstrate the use of the Mars Phoenix lander derived regolith scoop design with integrated sieves to acquire regolith samples and filter them to isolate size distributions of particles: *Scoop contents will be imaged before and after sieve motions, providing valuable insight for future payloads.*

Additionally, SAMPLR will extend the mission capabilities of adjacent instruments and the CLPS lander by enabling the following objectives:

4. Imaging, assessment, and/or mapping of the surrounding terrain and the lander or payloads using arm- and base-mounted visible light cameras (including stereo imaging).

5. Remove surface regolith using an arm-mounted scoop and study the variation by depth of geotechnical properties using the regolith penetrometer.

6. Deliver samples to other lander payloads using regolith scoop and integrated sieves.

7. Support turret mounted hosted payload (Heimdall) mission objectives with collaborative operations and instrument pointing: *Mounting with independent yaw enables flexible imaging such as panorama, lander inspection, and microscopic regolith.*

8. Demonstrate use of variable autonomy technologies to aid telerobotic missions.

Status: Following successful environmental testing and System Integration Acceptance Review with NASA in 2023, SAMPLR has been delivered into a storage phase. Originally slated to fly in 2023 on Masten Space Systems XL-1 (declared bankruptcy in 2022), SAMPLR has been re-manifested to a subsequent flight with lander selection expected in 2024. During the storage phase, the team will prepare for flight with Heimdall camera integration, operational demonstrations, and mission planning. SAMPLR will be operated fully by the Maxar team utilizing in-house advanced teleoperation and situational awareness tool suites.

Acknowledgements: The authors would like to thank NASA as well as SAMPLR Co-I's and partners including Dr. Chris Dreyer, Dr. Angel Abbud-Madrid, Dr. Barbara Cohen, and Dr. Aileen Yingst.

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Development and Optimization of Biopolymer-Amended Regolith Materials for Sustainable Extraterrestrial Landing and Launching Pads.

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Introduction: Permanent human settlement on the Moon (Fig.1.), and in the future, extend human presence to Mars [1]. To do so, repeated visits to the same location will be required and the construction of resilient and durable launching and landing pads (LLPs) will be essential (Fig.1.). The LLPs serve as a protective shield for the regolith surface during spacecraft operations, effectively mitigating the challenges posed by regolith ejecta and the formation of craters caused by rocket engines [2]. Hence, it is important to develop advanced extraterrestrial construction materials and manufacturing methods to ensure the safety and efficiency of our future space missions.

For the development, design, and production of materials for extraterrestial LLPs, it is important to consider the constraints associated with transporting supplies from Earth, given the high costs and limited payload capacity of rockets. In light of these challenges, scientists have proposed utilizing in-situ or locally sourced materials as a viable solution. Several different in-situ lunar regolith utilization construction methods have been proposed and studied, such as sintering [3], grading and compacting [4], waterless concrete, and polymer sprays [4] to name a few.

However, although certain construction methods have shown promising results, most have major drawbacks such as extremely high energy or water use, or the need for additional high-mass transportation, processing or fabrication equipment which would add to the cost and complexity of any mission [4-7]. Utilizing low-energy process-generated, naturally derived biopolymers as binding agents for regolith presents an alternative approach to create extraterrestrial biopolymer-regolith materials, potentially overcoming many shortcomings associated with other stabilization methods. The overarching research aim is to evaluate and optimize biopolymer-amended lunar and Martian regolith mixtures for their application in 3D printing materials used in constructing LLPs.

This study has shown that common biopolymers like Xanthan Gum, Guar Gum, and Beta Glucan can effectively bind extraterrestrial regolith, yielding materials whose properties are on par with conventional terrestrial concrete. The benefits of utilizing biopolymer-enriched regolith composites for LLPs over alternative technologies are manifold:

Safety and Risk Reduction: In extreme emergency scenarios, akin to the 'Apollo 13' incident, the edible nature of the binder offers an additional potential food source should the ship or habitat require a 'lifeboat mode'.

Feasibility: The biopolymer-regolith composite presents a straightforward approach with a technological readiness level surpassing many other proposed solutions.

System Integration: The biopolymer production process can be coupled with existing life-support systems, such as those for food and oxygen generation through plant cultivation, streamlining mission design and reducing expenses.

Energy and Water Efficiency: Unlike many other technology options, production of biopolymers is not energy-intensive, and it allows for the recovery of most water used since it relies on dehydration processes.

On-site production: Biopolymers are synthesized in situ, contrasting with some methods that necessitate the extraction and transport of rare minerals, thereby saving on logistical challenges and resources.

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Oscillating Heat Pipe Radiators for 425-575K Applications.

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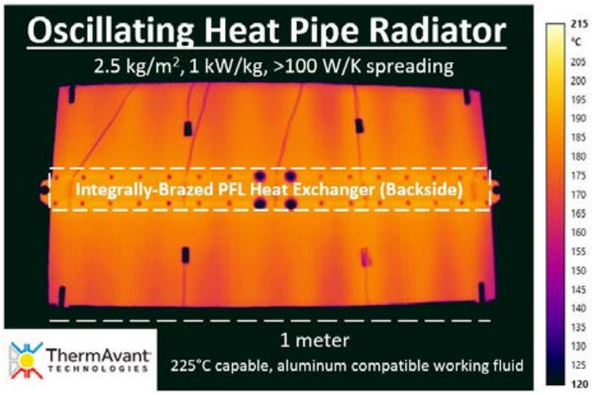
Introduction: Oscillating Heat Pipe (OHP) radiator panels have been recently developed to reject waste heat at intermediate temperatures from power conversion systems, applicable to lunar FSP and NEP missions. A background summary of content previous presented at LSIC [1] will be included, followed by final results of the phase II SBIR with NASA GRC.

Objectives:

1. Improve predictive modeling by further characterizing OHP behavior: thermal conductance and heat transport capacity limits
2. Optimize performance and mass to meet real-world requirements
3. Develop reliable manufacturing processes
4. Create technology transition paths

Phase II Accomplishments:

- High-performance aluminum-compatible working fluids (alkanes) demonstrated 125-220 °C, with OHP specific power exceeding 1 kW/kg at 200 °C
- Meter-scale aluminum OHP radiator manufactured with two-sided areal density <2.5 kg/m2, and integrally brazed pumped fluid heat exchanger (3.2 kg/m2 monolithic subassembly)
- Novel freeze-tolerant water mixture demonstrated up to 315 °C, with OHP thermal conductance 25x mass-equivalent titanium control
- NASA program to support TRL-5/6 TVAC testing of two intermediate temperature OHP radiators in 2024



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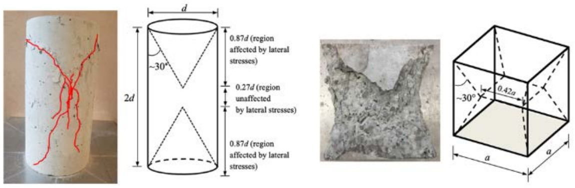
Identifying Gaps and Leveraging Terrestrial Civil Engineering Knowledge for ISRU Lunar Structures.

S. J. Dyke[1], A. Sharma[2], E. M. Mount[2], A. Bobet[2], and J. A. Ramirez[2], [1]School of Mechanical Engineering, Purdue University, 585 Purdue Mall, West Lafayette, IN 47907, [2]Lyles School of Civil Engineering, Purdue University, 550 W. Stadium Ave., West Lafayette, IN 47907. (Contact: sdyke@purdue.edu)

Introduction: Plans for establishing an infrastructure on the Moon involve the widespread use of indigenous resources, known as in-situ resource utilization (ISRU), to manufacture the building materials to be used [1]. NASA's Moon to Mars plans call for construction of reusable launch and landing pads. Several types of standards will be critical for building safe and durable structures on the Moon to serve as launch pads, habitats, shelters, foundations, blast shields, and perhaps even roadways. It is of paramount importance to remark that engineers, without experience working in an extreme environment such as the Moon or guidelines and codes developed for the same, are even more dependent on testing materials to develop the data needed to design and build safe structures that will perform as needed during their service life. We aim to highlight the gaps in knowledge that exist.

Problem Definition: The extremely hostile environment present on the Moon includes exposure to hard vacuum, thermal cycles, radiation, Moonquakes, micrometeorite impacts, and microgravity. The demands imposed based on these types of loadings should inform the performance needs of the structures, and thus should be used to identify the types of tests used in standards for Lunar structures. It will be important to leverage what has been established on Earth for construction on Earth. And translate that knowledge to explore how to adapt well-known structural materials (such as concrete) to meet the objectives associated with ISRU-based construction in the extreme environment present on the Moon [2].

Several similarities between regolith-based materials and concrete on Earth, such as brittle behavior and low tensile strength to compressive strength ratio, are evident. Thus, a reasonable initial assumption would be to consider the overall behavior of a structural material made of Lunar regolith by bonding, sintering, or other process to have similarities to that of terrestrial concrete. On Earth, the design of structural concrete is dependent on the concrete compressive strength specified by ASTM standards C31 and C39, which is used to derive structural properties for design per ACI 318-19 codes. However, it is important to note that the shape and size of the test specimens, typically cylinders in the US (see Fig. 1), and loading rate have a significant influence on the values obtained in a given test, and how those values should be treated for their use in design. Concrete gains strength over time as the cement hydrates, so the conditions for curing (i.e., temperature, moisture) affect the structural properties, aesthetics, and durability. Size effects, and scale effects, are both characteristics of these materials that need to be considered [2].



a. Concrete Cylinder Test Specimen b. Concrete Cube Test Specimen

Fig. 1 Influence of the loading plates on the stresses on well-established standard concrete cylinder (US) and cube specimens (Europe).

Perceived Gaps in Standards: Although there are several similarities between regolith-based materials and concrete on Earth, there are significant gaps associated with the use of regolith-based materials due to the extreme Lunar environment which are not considered for structural materials on Earth. Consider a Lunar landing and launch pad, for instance [goal LI-4]. Engineers must first quantify the expected hazards, mass, and payload. Then, the long-term behavior of the proposed material under extreme temperatures, radiation, hard vacuum, low gravity, Moonquakes, micrometeorite impacts, etc. is neccessary. To design for the mechanical loads and other solicitations that a landing and launch pad will be subjected to, a reliable assessment of the strength of the structural material when it reaches full strength, is needed, preferably using a large-scale facility with the capabilities to prepare and test appropriately-sized material specimens under the conditions expected on the Moon.

Acknowledgment: Based upon work supported by NASA under grant 80NSSC19K1076.

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Advancing Space Exploration: A Cyber-Physical Testbed for Space Microgrid.

Hasnain Nisar, Leila Chebbo, and Ali Bazzi, University of Connecticut, Storrs, USA (hasnain.nisar@uconn.edu)

Introduction: With the growing interest in space exploration, the need for advanced technologies to support future missions has become increasingly crucial[1-3]. Among these technologies, a highly reliable power system is needed to withstand extreme space environments and external disturbances. A Cyber-Physical Testbed (CPT) emerges as a valuable platform for testing and validating extraterrestrial microgrids, enabling the assessment of their resilience and performance under realistic conditions. This article presents a CPTas shown in Figure 1, Power Hardware in the Loop (PHIL) based, that incorporates physical components such as solar arrays, pressure and temperature controls, and electronic loads that mimic habitat loads, along with cyber components like nuclear generation, energy storage systems, and space habitat loads. This testbed provides a unique capability to thoroughly evaluate the behavior of the space microgrid under various load management scenarios, particularly in response to unexpected disturbances or disruptions. By emulating realistic conditions, the testbed allows us to analyze the power system's performance, assess its robustness, and identify areas for improvement in terms of power management, load prioritization, condition monitoring, and fault mitigation within the space microgrid.

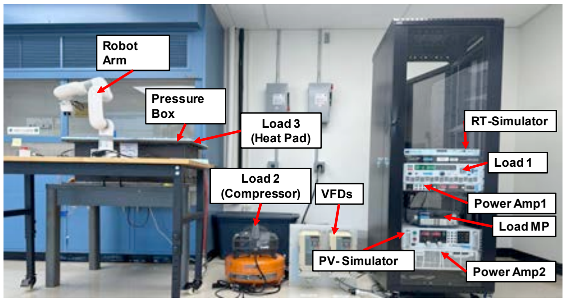
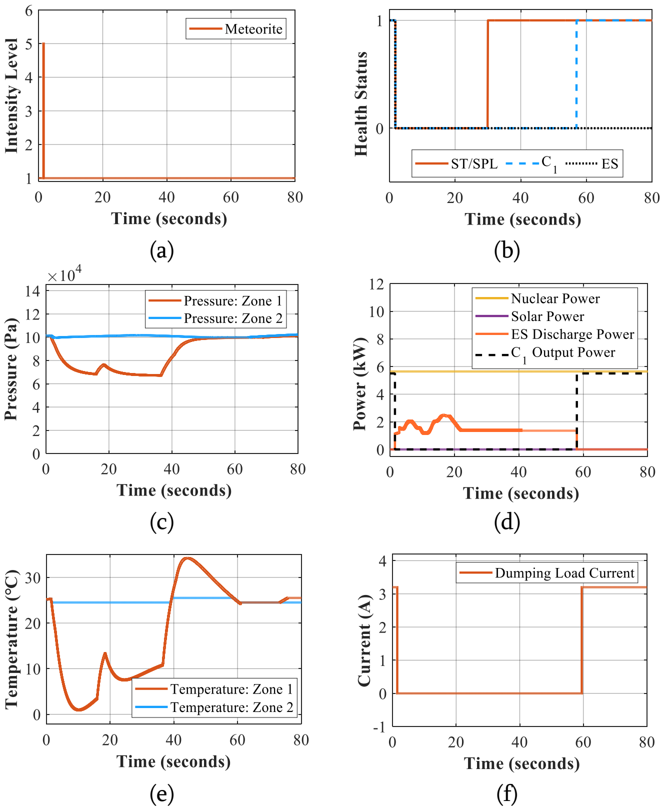


Figure 1. CPT including physical loads, PHIL, robotic arm for repair, and pressure box that mimics a habitat's dome; computer running the real-time habitat model is not shown.

Experimental Study:

A. *Meteorite Strike Hitting the Dome:*

To analyze the effect of meteorite strikes, a scenario of a meteorite impact on the structure of the pressure box was investigated using the implemented system. A 5 kg weight, representing the meteorite, was placed on the pressure box to emulate the impact. Scenario results are shown in Figure 2.



(a) (b) (c) (d) (e) (f)

Figure 2. Meteorite scenario results (a) Meteorite signal (b) Health status of ST/SPL, C$_1$ and ES (c) Pressure measurement (d) Power generation (e) Temperature measurement (f) dumping load current.

B. *Airlock Scenario:*

Investigating detection and assessment methods becomes crucial when there is a lack of breathable environment, air leakage, or a breach inside the dome since these circumstances directly affect the crew's safety [3]. Therefore, in addition to the meteorite impact on the pressure box, we also analyzed the scenario of an airlock breach. The results are not included because of the space limitation.

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Power Beaming Concept From Lunar Orbit to Small Lunar Science Assets.

S.R. Oleson[1], G.A. Landis[1], E.R. Turnbull[1], and the Compass engineering team, [1]NASA Glenn Research Center, 2100 Brookpark Road, Cleveland OH. Contact: steven.r.oleson@nasa.gov

Introduction: Science missions have been proposed which envision arrays of landed assets across the lunar surface, but operation of such assets across the two weeks of lunar night is difficult. The 354-hour night, with associated ~60 K temperature, requires either extremely large batteries or a radioisotope power system for survival and operation. An orbiting beamed power spacecraft is another option to provide this energy, thus removing the energy storage burden on the lander while still giving it years of science operations.

By using a photovoltaic (PV) array tuned to the laser wavelength (which will also produce power in sunlight) the mass and cost of large batteries or radioisotopes can be eliminated. Instead, a laser ‘beamcraft’ can distribute power to multiple landers in the night regions or inside a permanently shadowed region. While the end-to-end efficiency of the laser beam system is around 10%, the availability of sunlight in orbit and the cost savings from putting the power system in orbit instead of on the surface could make it competitive. While laser power beaming concepts have been proposed previously for lunar operations, a detailed concepts of operations and engineering design has not previously been done.

Concept: The beamcraft operates by gathering energy with solar arrays while in sunlight, stores the energy in an on-board battery, and then powers a laser beam which is then directed at each surface lander. A large-aperture, stable, and accurately pointed optic is needed to focus the beam to a few meters diameter to a laser-tuned PV array, which converts the laser light back into electricity to charge the lander’s battery for operations until the next beamcraft pass.

Case Study: The engineering case study assumed a baseline case in which 18 science landers were distributed at lunar locations from equatorial to polar latitudes, with half of them in shadow at any given time. Each lander requires 50 Watts average power during nighttime operation, including heating sufficient to keep the payload operational.

Lunar Coverage

Analysis of orbital view-factors showed that a constellation in 800-km polar orbit, with three beamcraft separated in right ascension by 60°, can provide coverage at all latitudes for a minimum of 24 minutes out of every 3 hrs (and, for most cases, more). To account for orbital perturbations by lunar mass concentrations and solar gravity, the orbits were propagated over 10 years of operations, showing stable operation with continuing coverage of landers at all latitudes.

If the latitude range of landers is restricted (for example, all the landers latitudes greater latitudes than 45°, or conversely, at lower latitudes), the number of beamcraft required can be reduced.

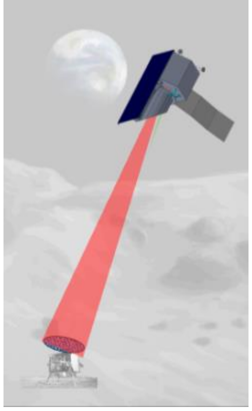


Figure 1: Beamed Power Concept

Beamcraft

A spacecraft was designed to carry a 7.6-kW commercially-available fiber laser with 1.06 μm wavelength (Figure 2). A 1.45-meter mirror (based on the Kepler telescope design) directs the beam, placing an illuminated spot of 3 meter diameter on the surface at maximum range. The 24-minute (minimum) illumination pass charges the lander’s batteries sufficient for operation until the next pass, nominally 3 hours, with extra battery capacity to give up to 24 hours of operation in case of a missed pass. Including growth allowance and margin, estimated mass of each beamcraft was 3500 kg.

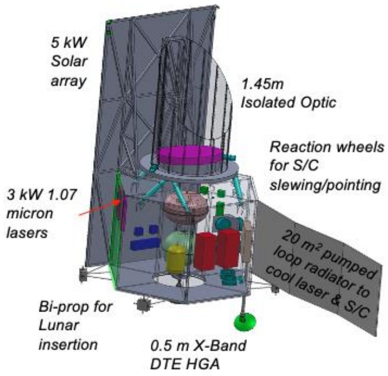


Figure 2: Beamcraft schematic

Conclusion: An engineering study showed that beaming laser power to lunar science assets to operate at multiple locations on the surface during the lunar night was feasible using a constellation of three small satellites in 800-km lunar orbit.

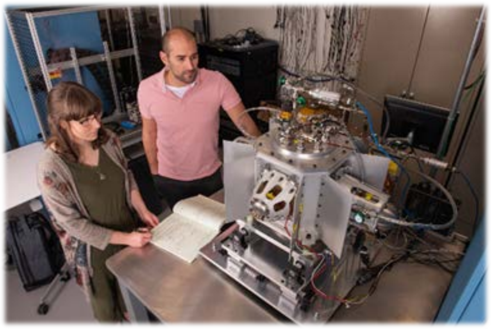
Status of Stirling-based Radioisotope Power System Development. S. M. Oriti[1], [1]NASA Glenn Research Center, 21000 Brookpark Rd Cleveland OH, (Contact: Salvatore.M.Oriti@nasa.gov)

Background: The unique challenges accompanying Lunar missions can be solved by radioisotope power systems (RPS), which can provide power regardless solar incidence, and also provide thermal power needed to survive the Lunar night. However, radioisotope fuel is not abundant so there is interest in high-efficiency conversion technologies such as Stirling convertors. They can be made to have no wear mechanisms which enables the long operating life needed for NASA missions. The RPS program at NASA Glenn Research Center has been investing in Stirling conversion technology development and system design[1][2]. A recent chapter of work has achieved several important milestones. The Stirling technologies developed for RPS are extensible to Fission Surface Power (FSP), as mulit-kW convertors based on the same engineering have been realized.

Recent Milestones: One of the dynamic power convertors manifesting recently is the free-piston Stirling convertor from Sunpower, Inc. named the Sunpower Robust Stirling Convertor (SRSC). This convertor can operate over a wide range of heat inputs and temperaures while maintaining high conversion efficiency. Performance has been demonstrated with heat input as low as 105 W_{th} and as high as 327 W_{th}. The hot-end temperature is nominally 700°C and the cold-end temperature operating range is 20°C to 175°C. Power output from a single unit has been demonstrated as high as 88 W_e with conversion efficiency up to 31%. These traits make the SRSC flexible for system integration with a multitude of heat sources.

A gamut of relevant environmental tests have recently been completed on several SRSCs to demonstrate TRL requisites. Thus far, several SRSCs have undergone performance mapping, in which the range of expected operating conditions were exercised, qual-level random vibration (7.7 g_{rms}), qual-level static acceleration (22.5g), qual-level thermal cycling (13 cycles). SRSC performance was shown to be the same within measurement tolerance after exposure to all these environments, which demonstrates it capable of a wide range of NASA missions. Efforts have also focused on accumulating runtime on the SRSCs to demonstrate life and reliability. Thus far a total 4 SRSCs have accumulated 5.5 years of operation amongst them, with the highest single-unit runtime reaching 1.9 years.

Progress has also been made on system designs that could utilize the SRSC. The topology which has been focused on is a convertor-redudant scheme that is as easy to integrate into a spacecraft as existing RPS. A contract with Aerojet Rocketdyne resulted in a design that incorporates 8 SRSCs with a central stack of 6 GPHS modules. This would permit failure of one pair of SRSCs without sacrificing power delivered to the spacecraft. This single layer of redundancy greatly increases system probability of success. Engineering models show this generator design would have a power output of 293 W_e, an efficiency of 19.5%, and a specific power of 2.6 W_e/kg. A generator-level test article to demonstrate this topology was recently brought online at NASA GRC, shown below. The article, named Stirling Generator Testbed, comprises 4 Stirling convertors with a central heat source. Even in its unoptimized state, it demonstrated 17% conversion efficiency.



Future Plans: Work will continue on the relevant environment testing to fully demonstrate TRL 5. This includes the more mission-specific environments such as shock, sine vibe, and EMI characterization. The SRSC has also garnered attention for commercial RPS applications. Work will also focus on the coupling of the SRSC with alternate heat source, such as Am-241. Am-241 is not as power dense as Pu-238, but has a 4-times longer half-life, and can be salvaged from European terrestrial reactor spent fuels. NASA has recently awarded a Tipping Point program contract to Zeno Power to develop a commercial RPS based on Am-241 and Stirling conversion.

References: [1] Oriti S. M. (2018) AIAA 2018-4498, [2] Wilson S. D. (2023) NETS 2023 Proceedings.

Making Aluminum from Lunar Regolith Simulants through Molten Salt Electrolysis.

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Introduction: The LISAP-MSE project. funded through NASA BIG Idea Challenge 2023, investigates a process developed to produce aluminum metal on the lunar surface via molten salt electrolysis. This process is outined in the flowchart as seen in Figure 1 below.

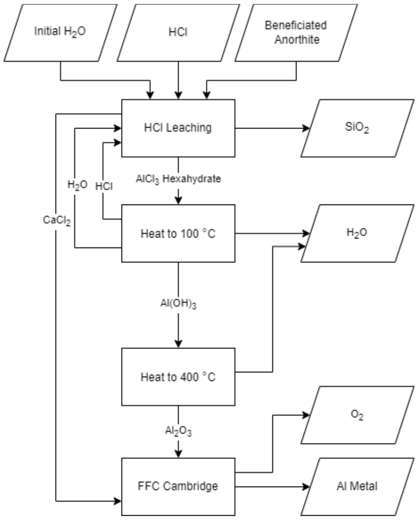


Figure 1: LISAP-MSE Flowchart

Methodology:

The LISAP-MSE project, will demonstrate the use of electro-deoxidation to reduce aluminum oxide (i.e., alumina) into aluminum and oxygen gas via electrolysis in a molten salt bath for the production of aluminum on the Moon. This process will be similar to that shown in Figure 2 below.

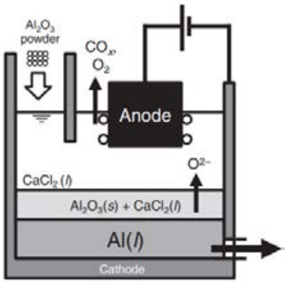


Figure 2: Aluminum Oxide Electrolysis [1]

It will be shown that with a steady supply of hydrogen chloride, this in-situ resource utilization (ISRU) method can supply almost all of the necessary materials consumed in electro-deoxidation to produce aluminum metal, oxygen, water, and silica from anorthite.

Results:

Leaching of the anorthite using hydrochloric acid and then two thermal decomposition steps were completed. Once the thermal decomposition steps were completed, XRD confirmed that approximately 37% of the crystalline solids present in the final product was with nearly all of the remaining material being calcium aluminates.

Next, the alumina was electrolyzed. Upon completion, a 6 milimeter diameter, metallic, spheroid was discovered in the testing apparatus (Fig. 3), it was removed and analyzed using SEM-EDS. Shown in Table 1 is the table of scan results at numerous spectrum sites taken on the materials surface.

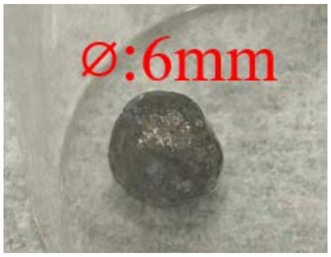
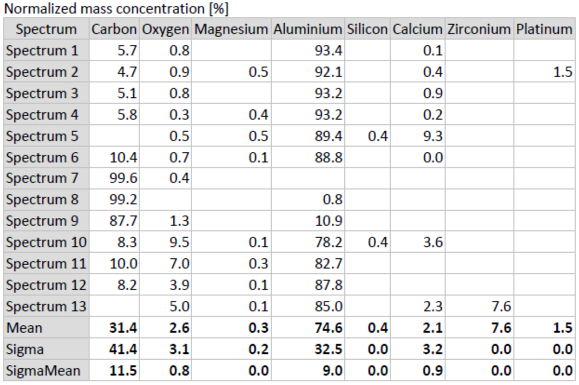


Figure 3: Metallic Spheroid Produced in Electro-Deoxidation

Table 1: SEM-EDS Spectra


Normalized mass concentration [%]

Spectrum	Carbon	Oxygen	Magnesium	Aluminium	Silicon	Calcium	Zirconium	Platinum
Spectrum 1	5.7	0.8		93.4		0.1		
Spectrum 2	4.7	0.9	0.5	92.1		0.4		1.5
Spectrum 3	5.1	0.8		93.2		0.9		
Spectrum 4	5.8	0.3	0.4	93.2		0.2		
Spectrum 5		0.5	0.5	89.4	0.4	9.3		
Spectrum 6	10.4	0.7	0.1	88.8		0.0		
Spectrum 7	99.6	0.4						
Spectrum 8	99.2			0.8				
Spectrum 9	87.7	1.3		10.9				
Spectrum 10	8.3	9.5	0.1	78.2	0.4	3.6		
Spectrum 11	10.0	7.0	0.3	82.7				
Spectrum 12	8.2	3.9	0.1	87.8				
Spectrum 13		5.0	0.1	85.0		2.3	7.6	
Mean	**31.4**	**2.6**	**0.3**	**74.6**	**0.4**	**2.1**	**7.6**	**1.5**
Sigma	**41.4**	**3.1**	**0.2**	**32.5**	**0.0**	**3.2**	**0.0**	**0.0**
SigmaMean	**11.5**	**0.8**	**0.0**	**9.0**	**0.0**	**0.9**	**0.0**	**0.0**

In this table, it can be seen that aluminum is present with very little oxygen. It can be concluded that aluminum metal was produced in this process.

References: [1] Kadowaki H. et al. (2018) *Journal of The Electrochemical Society,* 165.

The WIP FLEET: proposal for an orchestrated group of lightweight rovers and hoppers for International Lunar Resource Prospecting missions.

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Introduction: Volatiles in the lunar polar regions are of great interest for Science, Exploration and Commerce. Amongst them, water ice could become one valuable lunar resources, essential for future missions, permanent human presence and habitats on the Moon. Thus it is crucial to find, characterize and map lunar water accurately [1]. This involves the need “to quantify the nature, abundance, accessibility, extractability, and overall reserve potential” of this potentially game-changing resource, which, in turn, calls for designing and implementing a coordinated international resource evaluation/prospecting campaign [2].

Missions: There are several missions, some of them already operational, but mostly in preparation which aim to contribute to resource evaluation/prospecting. Ref. [2] lists nine such missions, four of these are orbiters and five shall conduct lunar surface operations. Among the surface missions there are three rover expeditions: NASA’s VIPER, the joint JAXA-ISRO LUPEX and the Canadian Lunar Rover Mission (LRM). VIPER and LUPEX are several hundreds kg, while LRM is planned to be around 30 kg [3].

Lightweight lunar surface mobility assets: Besides the Canadian LRM there is a growing number of low mass – roughly in the 5-35 kg range - robotic units (rovers/hoppers) providing lunar surface mobility and the ability to host payloads appropriate for resource prospecting.

Some examples are (no exhaustive list) are shown in the following tables:

Rovers	**Mass**
Micro Rover *Japan / Luxembourg, ispace, inc*	5 kg
MAPP *United States, Lunar Outpost*	5-10 kg
HiveR *Germany, NEUROSPACE GmbH*	5 kg (est.)
Cuberover class *United States, Astrobotic*	7-16 kg
Rashid *Emirates, Mohammed bin Rashid Space Centre*	10 kg
MoonRanger *United States, Carnegie Mellon University, Astrobotic*	13 kg

Hoppers	**Mass**
micro Nova Hopper *United States, Intuitive Machines*	35 kg
HopLa *Israel, WeSpace Technologies* - *in development*	8kg

The WIP FLEET (Water Ice Prospecting FLExible Exploration Teams): is a proposed assembly of low mass lunar rovers/hoppers to be organized for dedicated prospecting mission(s).

Participating organizations – the providers of the small surface assets - shall try to finance their unit (rover, hopper, payload) on their own. Since the development costs for most of these assets have already been mainly financed in dedicated projects, further exemplars could be manufactured quickly for much less cost (see the example of Lunar Outpost’s MAPP rover, [4]).

Lunar delivery for the FLEET could be ordered from a CLPS provider (Astrobotic, Intuitive Machines, Firefly, Draper/ispace, Lockheed Martin, …), financed by the participating countries space agencies (proportionally, according to the mass of the rovers/hoppers), or by any other means.

Coordination of the minimum required data sets and data quality, areas to be searched, landing site(s), data rights, etc. could be done by members of the still informal group of the advocates for an International Lunar Resource Prospecting Campaign [2].

Total cost of a WIP FLEET type prospecting mission (rovers, hoppers, payloads, lunar delivery, surface operations) is estimated below $300 million (ROM).

References:

[1] R. Weber, et al., Artemis Science Definition Team Report (2020), *NASA* [2] Clive R. Neal et al. (2024) *Acta Astronautica, 214,* 737-747 [3] G. R. Osinski et al. (2023) *54th Lunar and Planetary Science Conference,* Abstract #2487. [4] Tiny but Mighty Lunar Over” (2023), https://space.jhuapl.edu/stories/tiny-mighty-lunar-rover-moves-one-step-closer-launch Retrieved 3/1/2024.

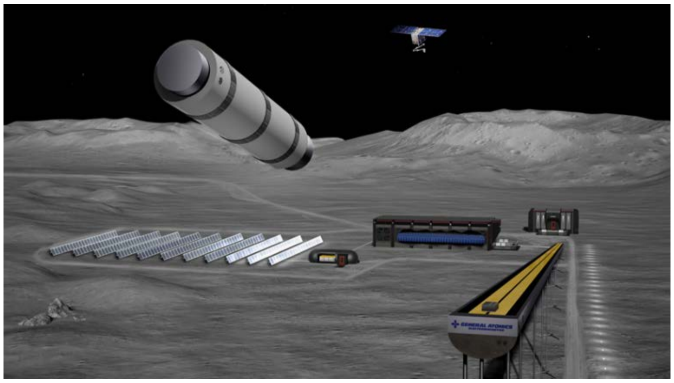
Lunar Electromagnetic Launch for Resource Exploitation to Enhance National Security and Economic Growth. Robert E. Peterkin, General Atomics Electromagnetic Systems, PO Box 85608, San Diego, CA 92186-5608. (Contact: Robert.Peterkin@ga.com)

Introduction: The lunar regolith is rich in oxides of useful elements including silicon, titanium, aluminum, and iron, and there are billions of tons of frozen water in the lunar polar regions [1]. A not-too-distant future lunar economy will make use of these lunar resources to resupply, repair, and refuel spacecraft in lunar orbit at lower cost than delivering terrestrial resources from Earth's deep gravitational well. Electromagnetic launch of material from the lunar surface can be significantly more efficient than conventional rocket launch that relies on chemical fuels that are imported from the Earth to the Moon [2].

The largest U.S. investment in high exit speed electromagnetic launchers has been for railguns. A railgun consists of a pair of parallel conductors (rails), along which a sliding armature is accelerated by the electromagnetic effects of a current that flows down one rail, into the armature and then back along the other rail. The lunar escape speed is much smaller than that of the Earth—2.38 km/s. This is a speed (≈Mach 7) that is routinely achieved with present-day state-of-the-art electromagnetic railguns including the U.S. Navy 32 MegaJoule (MJ) system.

A tubular Linear Induction Launcher is superior to conventional railguns because electrical efficiency is higher, acceleration forces are distributed over the armature body rather than concentrated on one end, and barrel erosion from arcing is avoided. Linear Induction Launcgers have been employed since 2021 on U.S. Ford-class nuclear aircraft carriers to launch military jets. To this date, the Electromagnetic Aircraft Launch System (EMALS) on CVN-78 [3] has executed over 20,000 successful aircraft launches. Lunar Electromagnetic Launch (LEL) based on the proven EMALS technology will enable 10-100 kg payloads to be delivered to lunar orbits at a high delivery rate that can be scoped to meet mission requirements and not be limited by receiving and storing chemical rocket fuel imported from Earth.

In a recent report performed with funding from the Air Force Office of Scientific Research, we quantified the advantages of LEL compared to conventional Moon-based chemical rockets, and we identified the critical set of technologies necessary for a reliable LEL infrastructure including energy storage and power delivery, a Mach 7 Linear Induction Launcher, and reuseable cargo containers [4]. We also identified supporting technologies that will need to be advanced in a manner that is consistent with the *2022 National Cislunar Science & Technology Strategy*, and we made recommendations on how to mature the technology necessary to launch extracted and processed lunar material into cislunar space to sustain a set of emerging space missions. Our LEL concept is illustrated in the image below. We will present these results at the LSIC 2024 Spring meeting.



References:

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[2] O'Neill, G. K. and Kolm, H. H. (1980). *Acta Astronautica* proceedings of the XXXth Congress of the International Astronautical Federation.

[3] O'Rourke, R. (2021). *https://crsreports.congress.gov/product/pdf/RS/RS20643*

[4] Peterkin, R. E. (2023) Lunar Electromagnetic Launch for Resource Exploitation to Enhance National Security and Economic Growth—*Final Report to AFOSR under Grant FA9550-22-1-0517*.

Magnetic Susceptibility Instrument for Magnetically Inhomogeneous Granular Mixtures.

C. T. Pett[1], A. Pick-Aluas[2], M. Taffel[2], C. Sunday[1], D. P. Lathrop[2], C.M. Hartzell[1], [1]Department of Aerospace Engineering, University of Maryland, College Park, [2]Institute for Research in Electronics and Applied Physics, University of Maryland, College Park. (Contact: pett@umd.edu)

Introduction: A plethora of apparatus exist for measuring the magnetic susceptibility of solid, monolithic materials. However, most naturally-occurring terrestrial and extraterrestrial granular samples are polydisperse mixtures composed of different elements with different magnetic properties. Variations in magnetic permeability across granular mixtures make it challenging to understand their bulk magnetic properties, so the range of magnetic susceptibility values for such mixtures are poorly constrained.

Inspired by recent asteroid sample return missions, a future close exploration of the metallic asteroid Psyche in 2029, and rejuvenated interest in lunar science, we designed a susceptibility instrument that could accurately probe a diverse catalog of magnetically, geometrically, and elementally irregular granular mixtures. Characterizing the magnetic susceptibility of samples on the Moon will help scientists understand the formation history of and space weathering effects on lunar regolith. Additionally, susceptibility measurements of lunar regolith will aid in the design of granular transport systems for excavation and ISRU since lunar regolith is magnetic [1], [2], [3].

In this work, we introduce an electronically simple, affordable, and portable susceptibility instrument that can be made in-house with a lathe and commercial off-the-shelf electronics [4]. The inductor coil (currently at TRL 4) can be submerged in a variety of granular mixtures in the lab or in-situ to quantify bulk inhomogeneous magnetic effects.

Theory: The relative magnetic permeability of a sample affects the inductance of a coil. To exploit this phenomenon, we used Eq. 1 to relate the permeability of the medium μ to the inductance *L* of a solenoid coil of radius *r* and length *l*, composed of *N* turns [5].

$$L = \frac{\pi \mu r^2 N^2}{0.9r + l} \qquad (1)$$

Neither the inductance nor the permeability were known a priori so we used Eq. 2 to obtain a separate value for the coil inductance L_{coil}. The measured angular frequency ω_{res} at which resonance occurs is a feature of the inductance L_{coil} and capacitance *C* in the circuit as in Eq. 2, which varies with material and volume fraction of mixture.

$$L_{coil} = \frac{1}{\omega_{res}^2 C} \qquad (2)$$

We can substitute Eq. 2 into Eq. 1 and solve for the permeability of the media. It follows that the permeability of the mixture relative to air less one gives the magnetic susceptibility χ_{coil} in Eq. 3.

$$X_{coil} = \frac{\mu_{mixture}}{\mu_{air}} - 1 \qquad (3)$$

Susceptibility Measurements: To make the coil, we wound motor winding wire on a lathe into a solenoid. We recorded values for the magnetic susceptibility of monodisperse mm-sized steel-brass (51200 Alloy Steel and 260 Brass) mixtures by submerging the coil in mixture as shown in Fig. 1. Then we compared our coil measurements to commercial Terraplus Inc. KT-10 meter readings and theoretical approximations [6] and report similar trends, but interesting differences. The instrument was validated by a measument of the permeability of air to within 0.045% of the theoretical value and a susceptibility measurement of brass mixture equal to the Terraplus Inc. KT-10 reading. Our coil was used in experiments to describe the avalanching behavior of magnetic grains [7]. The aim of future work will be to measure the susceptibility of lunar simulants inside a vacuum chamber.

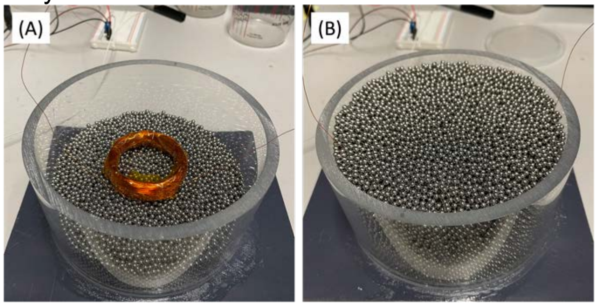

Figure 1: (A) Coil lay atop half the mass of steel bead mixture. (B) Coil submerged in total mixture, ready for measurement.

References: [1] R. R. Oder (1991) *IEEE Trans. Magn., 27 (6),* 5367-5370. [2] Y. Liu et al. (2007) *Am. Mineral., 92,* 1420-1427. [3] H. Kawamoto & R. Egawa (2021) *J. Aerosp. Eng., 34 (4)*: 04021026. [4] C. T. Pett et al. (Submitted Feb. 2024) *Review of Sci. Instruments*. [5] H. Wheeler (1942) *Proceedings of the IRE, 30,* 412-424. [6] K. Bai et al. (2018) *J. Appl. Phys., 124 (12)*: 123901. C. Sunday et al. (Submitted Feb. 2024) *Phys. Rev. E.*

Lunar Dust Removal using a Gecko Roller. C. T. Pett, C. C. Merrill, C. M. Hartzell, University of Maryland, College Park. (Contact: pett@umd.edu)

Introduction: Humans and robotic assets landing, exploring, and living on the Moon during the Artemis era will be immersed in a hazardously dusty environment. Lunar dust is notoriously abrasive and creates challenges for almost every lunar surface procedure, including negative optical and thermal effects. Mitigation technologies that quickly and effectively remove dust particles (down to microns in size) with minimal consumables, as well as meet tight mass, volume, and power constraints, are needed for future long-term lunar exploration. We present a novel technology to remove lunar dust from spacesuit, optical, and solar panel surfaces. The Gecko Roller is a handheld device that functions in the same way as a common terrestrial lint roller, but with an elastomeric gecko skin-inspired membrane replacing the adhesive sheet as shown in Fig. 1 (right). The synthetic gecko skin membrane is a silicone elastomer with micron-scale molded hair-like structures that increase the adhesion between the dust and the elastomer. The gecko roller requires no power when operated by an astronaut, but can become reusable via electrostatic cleaning if power is available.

Figure 1: (Top left) Topographical characteristics of gecko toes [1]. (Bottom left) SEM images of manufactured gecko skin microstructure [1]. (Right) Gecko roller after removing baking flour from a hard surface.

Results: Preliminary work has demonstrated that the gecko roller is able to effectively remove dust from hard surfaces (Fig. 2) as well as a spacesuit fabric swatch at lab temperature and pressure. The clean gecko roller was able to consistently remove over 90% of the lunar dust simulant from flat surfaces and spacesuit material at 1 atm.

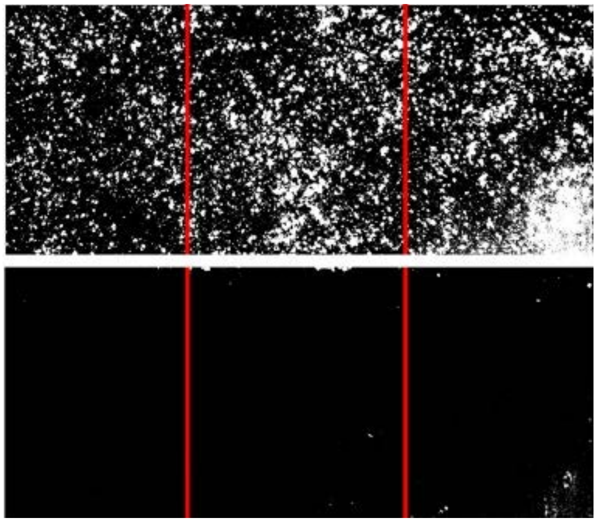

Figure 2: Top analyzed image of white baking flour on top of sur-face. Bottom analyzed image of top image after gecko roller cleaning. Red lines mark 1, 2, and 3 revolutions of the roller. Each box area is 5 in x 4 in.

Future Work: The gecko roller is currently at TRL 4. A recently awarded Lunar Surface Technology Research (LuSTR) 2023 grant aims to raise the technology to TRL 5 after testing in a lunar relevant environment in ultra-high vacuum at subzero temperatures.

References: [1] A. Parness et al. (2009) *J. R. Soc. Interface, 6*, 1223-1232.

Remotely Accessible Robotics Operations & Autonomy Testbeds for a Lunar Proving Ground.

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Introduction: The rise of commercial lunar missions has driven incentive for greater mission efficiency and low-cost operations. To support the lunar industry and help maximize success, Mission Control focuses on operations development and testing. Mission Control's HQ houses two robotic testbeds: one for surface mobility, and one for robotic manipulator applications. Both robotic testbeds are unique for the wider Lunar Proving Ground community as they are not just used by our company's R&D teams, but are available for use remotely by anyone with an internet connection via our web-based operations platform Spacefarer™.

Moonyard: Indoor Lunar Testbed

Mission Control's 4000ft^2 Moonyard provides a one-of-a-kind indoor test area to support year-round testing of robotic vehicles in a controlled environment with lunar terrain that is visually high-fidelity. It includes geologically relevant features and landscapes that can be reconfigured to reflect volcanic, polar, highlands, or mare terrain. Our Moonyard test facility currently houses six test rover platforms that can be used for a variety of purposes from pre-flight operations testing, payload integration and data collection, and overarching mission concept design, testing and validation.

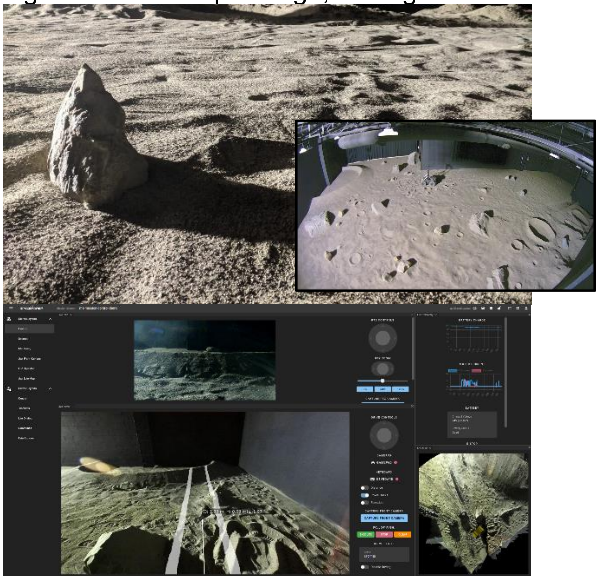


Figure 1*. Top: An image taken from a micro-rover in our Moonyard; inset: full view of the Moonyard from a static camera. Bottom: View of the Moonyard through a rover operated with Spacefarer™.*

Orbital Autonomy Lab: Mission Control's Orbital Autonomy Lab (OAL) is designed to facilitate TRL-6 level development and testing of robotic manipulator mission operations software, guidance, navigation and control algorithms, and rendezvous and proximity operations sensors. The OAL consists of two 6 Degrees of Freedom robotic arms and allows teams to test and validate operations scenarios and generate high-fidelity datasets for training machine learning models. It can be adapted and used for several spaceflight applications from orbital robotic satellite servicing to lunar surface robotics for tasks such as excavation, construction, cargo handling, and system inspection.

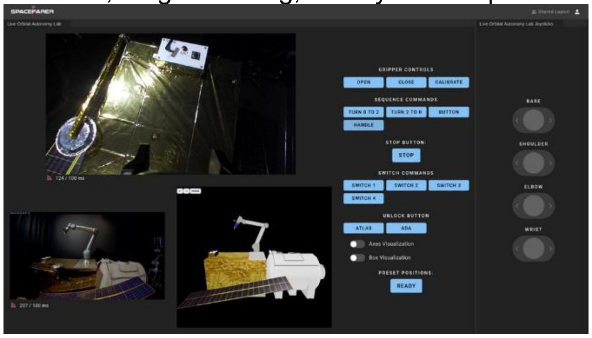


Figure 2. *The Orbital Autonomy Lab seen through our remote operations platform Spacefarer™.*

Use for Lunar Mission Preparation

Mission Control's Moonyard has been used by our R&D teams to collect high-fidelity micro-rover imagery [1] that was then labeled and used to train our MoonNet [2] deep learning model that flew to the Moon in 2023 onboard the ispace Hakuto-R mission as a technology demonstration, supported by the Canadian Space Agency. This was an essential step in our progression to TRL 9 for machine learning flight software. Our Moonyard has also been used and continues to be used by rover and instrument development teams to collect data, validate operations concepts, and prepare for upcoming manifested lunar rover missions.

Both our Moonyard and our Orbital Autonomy Lab are also used for educational and outreach programs, whereby students can remotely learn about and participate in a mock Moon or Mars robotic mission leveraging our robots in our analogue environments.

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

References: [1] Stefanuk et al., (2021) AIAA ASCEND [2] Cross et. al. (2023) ASTRA

The LEADER: Lunar Equatorial Daylight Exploration Rover Mission Architecture. A. B. Madhu Thangavelu [1] and C. D. Saba Raji [2], [1] University Of Southern California, mthangav@usc.edu, [2]University Of Southern California, Sraji@usc.edu. (Contact: mthangav@usc.edu)

Introduction: The LEADER Lunar Equatorial Daylight Exploration Rover traverse mission concept proposes an exciting alternative to Artemis III. The LEADER proposal plans to return crew to the Mare Tranquillitatis region to explore the pits and conduct a traverse to the Apollo 11 site to survey the landing site in order to assess, protect and preserve the historic site and its contents. The LEADER mission is proposed as a phased, evolutionary dress rehearsal to test the capabilities and performance of commercial space transportation systems as well as lunar surface operations systems before attempting a much more complex polar landing and associated activities.

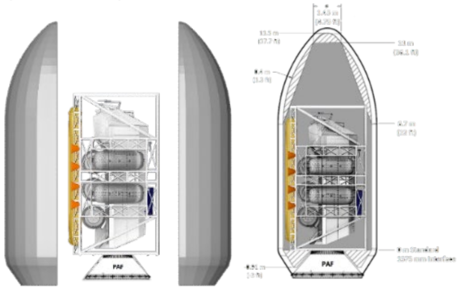
The LEADER mission is built around certain core principles. They include Low Earth Orbit(LEO) integration and staging at ISS, enhancing safety through integrated design, simplifying crew transfer EVA needs between transit, lunar lander and surface vehicles that also provides instant mobility and flexibility upon lunar landing, emphasizing efficiency in lunar surface exploration.

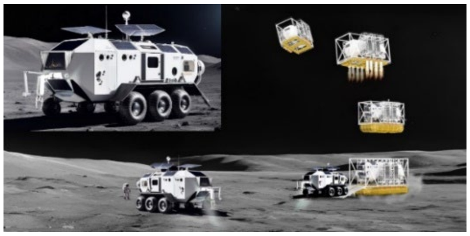
Innovative systems proposed for the LEADER mission include modular, fully reusable propulsion systems and the use of a thrust pallet for cislunar transport stages and controlled rupture airbag landing systems for final descent and touchdown stage to curtail debris production by the heavy LEADER lunar rover.

Integration of the LEADER mission in LEO, assisted by the crew of of ISS has several benefits including enhanced global participation and crew adjustment period in the LEADER mission that outweigh the Earth-Moon celestial alignment limitations.

The ability of the LEADER pressurized rover to serve both as a habitat module and a rover during the entire 2-week mission will enable astronauts to explore sites along the mare traverse while being monitored from orbit, without the need to frequently return to a lander, maximizing the productive output of the LEADER mission and paving the way for a sustainable human presence on the Moon.

This is an ongoing study and several trades among the elements are being assessed. Aspects of the LEADER mission plan and profile along with systems and operations being studied are outlined.





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[5] Thangavelu, M., Arunsalam, A., Asher, J., Benn, C., Cordero, N., George, R., Miller, R., Tallapragada, S., Ulusoy, U. (2020) USC ARTEMIS Project: Maximum Impact (MAXIM) Moon Mission Tribute to Apollo, IAC-20,A3,1,10,x61119

LunAR-X: Lunar Autonomous Regolith Excavator.

D. Tyagi[1], H. Ravichandran[1], V. Mohta[1], A. Senathi[1], V. Chervi[1], and W. Whittaker[1], [1]The Robotics Institute, Carnegie Mellon University, 5000 Forbes Ave, Pittsburgh, PA 15213, USA. (Contact: hravicha@cs.cmu.edu)

Introduction: Establishing a sustainable human presence on the Moon is critical for expanding our exploration capabilities within the solar system. Achieving this objective necessitates the efficient utilization of In-Situ Resource Utilization (ISRU) [1], leveraging readily available lunar resources. However, acquiring large quantities of lunar regolith, the soil-like surface layer, presents significant challenges. Manual operations are not only labor-intensive and inefficient but also inherently risky in the harsh lunar environment. Consequently, constructing lunar infrastructure mandates the development of autonomous robotic solutions [2], mitigating the dangers and limitations associated with human space missions. Addressing this need, we present the Lunar Autonomous Regolith Excavator (LunAR-X), a system designed to demonstrate proof-of-concept autonomy for lunar construction tasks. LunAR-X is capable of autonomous excavation, transportation, and deposition of regolith-like materials for berm construction.

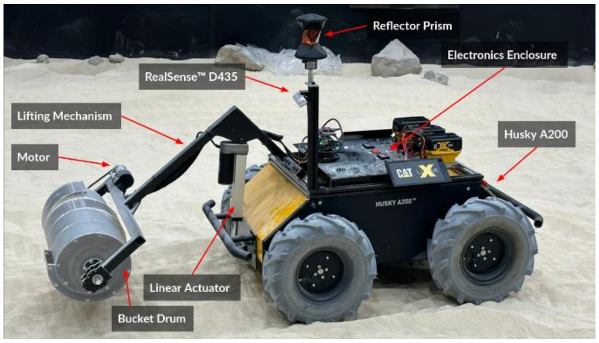

Figure 1. LuNAR-X system

Technology: Inspired by NASA's Regolith Advanced Surface Systems Operations Robot (RASSOR) [3], LunAR-X employs a bucket-drum excavator design specifically suited for low-gravity environments where conventional traction-based excavation is ineffective. The system precisely localizes without GPS, using a total station, IMU, and wheel encoders. A bi-level task planner is implemented to minimize total operational energy and restrict motions to maintain traversability. Feedback from the drum motor current is used by a cascaded control module to regulate tool depth for efficient excavation in uneven terrains. Furthermore, a visual servoing technique is employed for precise material deposition and to ensure accurate berm construction. The system estimates the task progress online and dynamically adjusts the high-level plan to handle uncertainties during task execution. Finally, we evaluate the built berm by computing accuracy metrics on the generated map of the manipulated terrain. Our code is made available online at: https://github.com/Lunar-Autonomous-Regolith-Excavator/LunAR-X.

Figure 2. Fully constructed berm

System Performance: The system demonstrates the successful construction of berms at least 15 cm tall and 1.6 m long within 30 minutes, with each excavation and deposition cycle yielding approximately 7 to 8 kilograms of material.

References:

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Active Phased Array Technology for Lunar Communications. J. T. Robison, CesiumAstro, 13215 Bee Cave Pkwy., Suite A-300, Austin, Texas 78738. (Contact: james.robison@cesiumastro.com)

Introduction: A robust and flexible communication infrastructure is critical to establish a sustainable human presence on the Moon. Active phased array (APA) antenna technology shows great promise for lunar communications due to its use of high-gain, electronically steerable beams that offer enhanced flexibility and efficiency as compared to traditional antennas. Extreme temperatures, vacuum conditions, and low-gravity effects are but a few of the challenging environmental conditions found on the lunar surface for which APAs are suitable. Further, APAs offer a pathway toward establishing reliable, high-speed communication links between Earth and lunar assets, which facilitates scientific research, commercial activities, and human exploration endeavors. APA applications include connecting surface assets with orbiters, communications on-the-move (COTM), and direct-to-Earth (DTE) connectivity. The integration of APAs into future lunar missions will revolutionize the lunar communication architecture and enable a new era of lunar exploration and discovery.

Mechanical Recycling of Textiles in Microgravity – The future of Textile recycling during Space Exploration and Human Presence in the Moon.

Sara Rosberg[1] and Marcelo Boldt[2], [1]Transforming Textiles AB, info@transformingtextiles.com, [2]Transforming Textiles AB, germanboldt@gmail.com. (Contact: info@transformingtextiles.com)

Introduction: The future of space exploration envisions a sustainable human presence and exploration of celestial bodies such as the Moon or Mars. The ARTEMIS Program, currently gaining international support, represents a significant step towards achieving this objective.

In this context, it is evident that sustainability will play a critical role in every exploration program, serving as the cornerstone for establishing a long-term human presence and facilitating future expansion into new worlds. However, this goal presents substantial challenges that necessitate a re-evaluation of activities that are conventionally taken for granted on Earth.

For example, issues such as laundry; clothing recycling; manufacturing; and waste disposal, pose complex problems, that must be addressed by the ARTEMIS Program to enable humanity's multiplanetary existence.

While research has been conducted on the recycling of textile fibres, further advancements are required in this field, especially regarding mechanical recyceling. This study aims to address and analyse the question of mechanical recycling of textile fibres in space, incorporating new smart technology integrations, taking into account factors such as micrgravity and resource scarcity.

By leveraging expertise in both Textile Engineering and Space Engineering, our objective is to explore this task, and develop a technical project roadmap for future implementations.

Furthermore, this study will introduce Sense-Tex, a sustainable 5-fiber yarn that can be fully recycled and manufactured in space. When integrated with sensors, this yarn has the ability to measure physical parameters such as humidity and temperature in real-time, among many others.

In addition to Sense-tex being a health-enhancing fabric, it is also produced without chemicals in the manufacturing process, which would otherwise pose problems in space. Both on the manufacturing and recycling aspects.Replace these instructions with the text of your abstract. Do not delete the section break above. Please verify that your paper size is set to U.S. letter, 8.5" × 11", before submitting your abstract. Page margins are set to be one inch on all sides. Tables or figures may be included but must fit within the 1 page limit. Abstracts should be submitted in pdf format.

Digital Formats: Any image file format that can be imported into this file will be acceptable for publication. Please use smaller-format files, when it provides acceptable resolution (~300 dpi at printing size).

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References: Use the brief numbered style common in many abstracts, e.g., [1], [2], etc. References should then appear in numerical order in the reference list, and should use the following abbreviated style:

[1] Author A. B. and Author C. D. (1997) *JGR, 90,* 1151–1154. [2] Author E. F. et al. (1997) *Meteoritics & Planet. Sci., 32,* A74. [3] Author G. H. (1996) *LPS XXVII,* 1344–1345. [4] Author I. J. (2002) *LPS XXXIII,* Abstract #1402.

E-Powered Micro Vehicles™ for use on Moon/Mars xEVA's.

Keith M. Rudofsky, Micro Vehicle Technology® LLC
3032 East Commercial Blvd. #111
Fort Lauderdale, FL 33308
Contact: Keith.Rudofsky@MicroVehicleTechnology.com

Introduction: Micro Vehicle Technology® LLC is developing the astronaut's "Go-To" mobility vehicles for human and equipment transport on the Moon and Mars. E-Powered Boots followed by an E-Powered Hands-Free Utility Cart, will prove to be an obvious choice for getting around, instead of, or in addition to, walking or driving a large 4-wheeled multi person lunar buggy.
"Consider Ants. Ants convoy. They don't carpool."

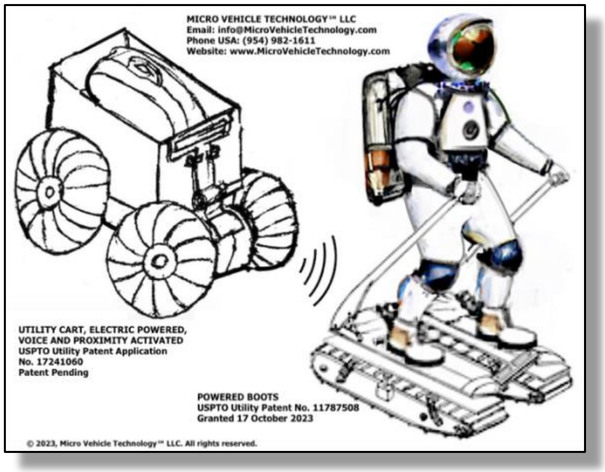
Micro Vehicle Technology® LLC is seeking patent licensee and manufacturing partners to help develop and tailor Micro Vehicles™ to NASA's Artemis xEVA ConOps, as well as other SBIR/STTR topics of need.

The Innovation: *What are Powered Boots?* As electric motors, batteries, and electronics become smaller, lighter in weight, and more power dense, it becomes possible to package these components compactly within an envelope essentially the size of a pair of boots. For stability and safety, the pair of boots includes a four-bar linkage connecting chassis and handlebars that allow carving through turns. The result is an easy to learn, yet rugged multi-terrain Micro Vehicle™.[1]

What is an E-Powered Hands-Free Utility Cart? The E-Powered Hands-Free Utility Cart follows a person by voice commands and proximity sensing. The E-Powered Hands-Free Utility Cart includes a standard base with propulsion and control unit, and a quickly changeable carrying bin for the many different uses that will be realized.[2]

Benefits of Micro Vehicles™: How do Micro Vehicles compare with the state of the art?

- Launch weight may be much less for multiple personal Micro Vehicles™ compared to a single multi-passenger rover.
- Multiple personal Micro Vehicles™ may be easier to package, distribute weight, and subsequently deploy from a surface lander or cargo vehicle compared to a single multi-passenger rover.



- Powered Boots Micro Vehicles™ reduce the need for astronauts to walk and sit, thus mitigate health and constricted spacesuit concerns.
- Use of Powered Boots Micro Vehicles™ will cut out much time from the already planned Artemis III xEVA Con Ops walking range or may allow additional activity and greater exploration distances than currently planned.
- Multi-passenger rovers can be equipped with Micro Vehicles™, therefore, in case of rover failure, mitigate a lengthy and physically exhausting walk back scenario.
- With each astronaut using their own personal Micro Vehicle™ like ants, swarm logic can be implemented, therefore surface travel routes, colonization, and operations, and emergency contingencies can be expedited and optimized for efficiency and fault tolerance.
- ChatGPT believes using personal micro vehicles™ for lunar colonization will absolutely mitigate dust and optimize productivity!

[1] Rudofsky K.M. (2021) *USPTO, Patent No. 11787508 - Powered Boots*

[2] Rudofsky K.M. (2021) *USPTO, Application No. 17241060 Utility Cart, Electric Powered, Voice and Proximity Activated.*

Regolith Conveyance, Transportation, and Storage Systems for Lunar and Martian Missions.

Süleyman Salihler, Polimak Process Technology (Contact: ssalihler@polimak.com)

Introduction: This abstract outlines the development of ISRU technologies designed for the efficient management, transport, and processing of space resources. Key activities include: (1) Conveying regolith from excavation zone to processing facilities on Lunar / Martian surface, (2) Continuous feeding regoith to analysers and processing devices on lunar landers and rovers, (3) Conveying large volumes of regolith for lunar construction works, (4) Stockpiling and contained storage of raw materials, (5) Filling flexible or inflatable fabric materials to build structural elements for lunar architecture, (6) Transporting raw materials between celestial bodies, vehicles, space shuttles, storage vessels etc.

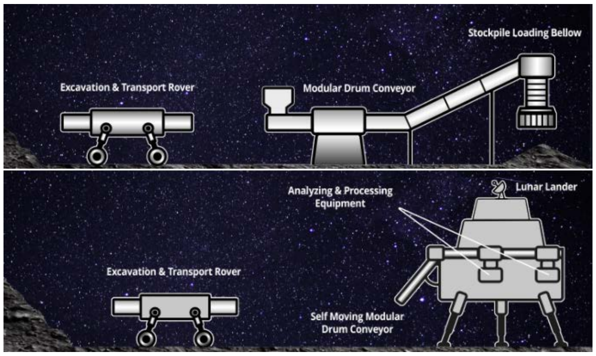


Figure 1. Lunar mission scenarios showing regolith excavation and stockpiling (top), continuous feeding of regolith analyzers on lunar lander (bottom).

Overview: Polimak has developed several systems and technologies to offer solutions for regolith handling, including conveying, transportation, storage, and dust containment tasks. One such system addresses these challenges through modular, motor-driven rotating drums with internal flights, adaptable for varying distances and routes. Regolith is transported within these drums, minimizing abrasion and contact with moving parts. This system supports various conveyance methods and can also be mounted on lunar rovers for secure regolith transportation and straightforward transloading. This innovative design significantly enhances energy efficiency and utilization by at least 50% compared to lunar rovers, which spend a substantial portion of their operational time returning empty to the loading area. By strategically deploying a system where 90% of the conveying route is managed by this modular setup, and only relying on rovers or excavators for the critical remaining 10%, an exceptionally efficient method of regolith handling can be achieved.

Latest Updates: The project progresses through stages of technology development, testing phases, and identifying collaboration opportunities, in a sequential manner, as follows: (1) Successfully tested modular drum conveyors for transporting materials across various distances and directions, (2) Developed a rover with a built-in drum conveyor for effective regolith excavation and transport, currently being tested, (3) The rover and conveyor are currently undergoing tests in the lunar testbed of PTS Space, Germany, to demonstrate a real use case involving excavation, transport, conveying, and processing of regolith.

Figure 2. Rover equipped with an integrated modular drum conveyor, undergoing tests for regolith excavation and transloading to a fixed modular drum conveyor system.

Upcoming Technology Demonstrations: (1) Regolith excavation and transport via a rover's onboard modular drum conveyor, leading to a fixed conveyor system for construction stockpiling. A dust-preventing telescopic chute, under development, will be featured. (2) Continuous, simultaneous feeding of processing devices on landers or rovers with a modular drum conveyor, set for lunar testbed trials. (3) Introducing storage and transport containers designed for low / zero gravity, highlighting their filling, transport, and discharge capabilities. (3) The filling and sealing of regolith into flexible fabrics and inflatable structures for efficient containment. (4) Use of swarm rovers with modular drum conveyors to form an adaptable, extensive conveyor system. (5) Advancing drum conveyor technology through 3D printing of components from regolith simulants.

Mini-ROXY: The Next Step Towards an Efficient Method for Oxygen Extraction from Regolith. Achim Seidel[1]; Emanuele Monchieri[1]; Ulrich Kuebler[1]; Uday Pal[2]; Georg Poehle[3]; Christian Redlich[3]; [1]Airbus Defence and Space, Germany; [2]Boston University, USA; [3]Fraunhofer IFAM, Branch Lab Dresden, Germany (Contact: achim.seidel@airbus.com)

Introduction: ROXY (Regolith to Oxygen and Metals Conversion) has been specifically conceived for oxygen and metal extraction from lunar regolith [1]. Invented by Airbus, it is based on a long heritage of the SOM (Solid Oxide Membrane) process developed by Boston University [2]. ROXY is a molten salt electrolysis process with fluoride salts & SOM anodes, operates at a low reaction temperature (850°C), includes built-in state-of-the-art O_2 separation, purification, and measurement, and thus allows the direct production of oxygen. With the advanced Mini-ROXY concept, the reactor vessel is eliminated and a YSZ (yttria stabilized zirconia) tube is used as a crucible, leading to a more optimized and compact design with improved performance-to-mass and power ratios [3].

Mini-ROXY is the result of a radical simplification exercise and is the next step towards resource efficiency. A Mini-ROXY lunar demonstrator is under development in the frame of a project sponsored by the German Space Agency DLR in preparation of a Mini-ROXY lunar demonstration mission. The Mini-ROXY lunar demonstrator is therefore designed to be compatible with the Payload Interface Requirements defined in PRISM-3 call for a generic CLPS lander [4].

Mission objectives are (a) to understand the properties of the lunar feedstock by determining its rheological, physical, mineralogical, and chemical properties; (b) to investigate the regolith reduction process and its performance/limitations when operating under lunar environmental conditions, in particular addressing the impact of reduced gravity, vacuum, build-up of electrostatic charge, and true regolith; and (c) to characterize the generated product, particularly the amount and purity of oxygen produced.

The key science objectives of this mission are therefore to characterize and understand the physical and chemical processes associated with the following steps:

1. Transfer of regolith from inlet of Mini-ROXY demonstrator to the reaction zone (called “cartridge”).
2. Regolith beneficiation.
3. Mineralogical and/or elemental characterization of the regolith.
4. Design of an optimized salt electrolyte for regolith reduction.
5. Implementation of suitable diagnostics for an in-depth characterization of the reduction process.
6. Transfer of processed regolith out of cartridge.

A bi-national US-German science team is addressing these objectives. The project is searching for additional parties that are interested in scientific collaboration for a Mini-ROXY lunar demonstration.

References:

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Careful Spectrum Planning to Enable Diverse Cis-lunar Activities. C. C. Sham[1] and K. K. Clothier[2], [1]NASA Johnson Space Center, 2101 E NASA Pkwy, Houston, TX 77058, [2]Teltrium, 6406 Ivy Lane, Suite 210, Grenbelt, MD, 20770. (catherine.c.sham@nasa.gov)

Introduction: With the recent successful landings of the Japan Aerospace Exploration Agency's(JAXA) SLIM lander and Intutive Machines' Odysseus lander, humanity's return to the Moon is well underway. This Artemis era will be characterized by collaboration and innovation as NASA, our commercial partners, and other international civil space agencies all work together to return humans to the Moon, and build a long-term presence there.

None of these missions, however, will be able to achieve their exciting and inspirational objectives without wireless communications and navigation capabilities. Lunar missions need to send and receive a mix of scientific data, spacecraft health and telemetry, navigation data, command and control data, and possibly more. These communications and navigation needs rely on the wireless transmission of information via the electromagnetic spectrum. In this new era of both public and private lunar exploration, spectrum requirements are becoming even more complex, as missions also envision live, or near real-time video and audio streams to support public outreach, astronaut safety and well-being, or for remote operation of robotic systems. Effective RF spectrum planning and regulatory considerations can only successfully enable the exciting and groundbreaking missions envisioned with early, open and frequent information sharing between mission planning and spectrum planning communities.

This presentation will discuss the role of NASA's Lunar and Human Spaceflight Spectrum Manager, a role established to serve as the central focal point for spectrum pre-coordination of lunar region activities carried out by NASA, other U.S. federal government agencies, other international civil space agencies, and commercial entities who elect to participate in this technical pre-coordination process. Through this Lunar and Human Spaceflight Spectrum Manager role, NASA continues its strong tradition of active and constructive engagement on spectrum issues with our other government partners, our international partners, and our growing number of commercial partners.

NASA's Lunar and Human Spaceflight Spectrum Manager works at all levels, across multiple stakeholder communities to ensure technical rigor in regulatory and policy discussions, the effective and timely information exchange as part of standards and architecture development processes, and regular technical information exchange to facilitate effective pre-coordination of frequeinces to avoid harmful interference.

This presentation will also discuss lunar-related spectrum regulatory activities at the International Telecommunication Union (ITU), and the within the US domestic regulatory process with the National Telecommunications and Information Administration (NTIA) and Federal Communications Commission (FCC).

It will also describe ongoing collaborations through groups such as the Space Frequency Coordination Group (SFCG) to develop relevant Recommendations and provide technical spectrum expertise in the development of international regulations, standards, and policies such as the LunaNet Interoperability Specification [1], a collaboration between NASA, the European Space Agency (ESA) ESA, and the JAXA. Through this collaborative process, a detailed Lunar Spectrum Architecture has been developed and continues to be refined. NASA encourages all entities planning activities on or around the Moon to consider the communication and navigation specifications, especially the recommended spectrum bands, described in LunaNet when planning for their lunar missions' communications and navigation support to ensure spectrum compatibility amongst the increasing number of systems planned in the lunar vicinity in the coming years.

Collaboration between mission planning and spectrum planning communities, to include a diverse range of stakeholders involved in cislunar activities will be critical to the successful development of a a communication and navigation architecture that enables the kind of reliable and fully interoperable connectivity that humanity has come to expect in the 21st century – on and around the Moon.

References:

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Exploring Nuclear Microreactors for Planetary Tunnel Boring Machine Applications. John C. Smith, Jr., PE[1] and Dr. Jeffrey C. King,[2]; [1]Phd Candidate, Colorado School of Mines, 2029 Epsilon Court, Orange Park, FL 32073, [2]Professor, Nuclear Science and Engineering Program, Department of Metallurgical and Materials Engineering, Colorado School of Mines, 1500 Illinois St., Golden, CO 80401 . (Contact: john-smith@mines.edu)

Introduction: *"Prediction is very difficult, especially if it's about the future." – Niels Bohr*

Our willful evolution into a space faring civilization is scientifically vital, would provide us with infinite resources and scientific breakthroughs to modernize our physical economy and infrastructure, and would be a lot of fun, and is essential for the future evolution of the human species.[1] Raw material and industrial development are the "fuel" of space development. Derived leaps in physical economic productivity, in the productivity of labor, are the "profit"!

Lunar and deep space missions will require power-intensive bases, mining, and construction activities. Construction of subsurface facilities by tunneling is proposed to construct bases and facilities to mitigate harsh surface conditions such as surface solar radiation, near vacuum, micrometeorites and meteorites, and wide diurnal temperature swings.[2] Building such subsurface infrastructures are energy intensive, while various scenarios can be considered for the selection of the proper construction method. Use of Tunnel-Boring Machines (TBM) has been proposed to facilitate automation of the operation and to enable construction with minimal human intervention. TBM's may be good choices for building lunar subsurface habilitation, research, industrial and recreational facilities, and as a way of connecting the bases and potential large spaces such as lava tubes.[3]

Operations of heavy construction sites, especially with TBM's, will require lightweight, energy dense, dependable, reliable, and resilient power supplies.[4] We compare past, present, and proposed fission and fusion micro reactor designs and solar plants.[5] Issues with current TBM designs and heat transfer challenges are also reviewed.

.

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Community Science on the Moon with GLEE. B. Sobhani[1], [1]Coloardo Space Grant Consortium, University of Colorado Boulder, 520 UBC, Boulder, CO 80309, (Contact: Barbra.sobhani@colorado.edu)

Introduction: The Great Lunar Expedition for Everyone (GLEE) is a catalyst for a new generation of space missions and explorers from around the world. GLEE, initially funded through the Artemis Student Challenge, is a unique mission to demonstrate a new data collection strategy using a large network of inexpensive, student designed, sensing packages on the lunar surface. The GLEE mission will deploy hundreds of solar-powered, 5 cm x 5 cm sensing boards, called LunaSats, over approximately 300 square meters on the lunar surface. Each LunaSat will autonomously record and transmit thermal, magnetic, acceleration, and regolith characterization data using a radio mesh network. The LunaSat network will allow for the investigation of magnetic anomalies, lunar seismicity, micrometeorite impact rates, thermal properties and characterization of the lunar regolith in the deployment area.

Student Engagement: GLEE is engaging thousands of high school and higher education students and faculty around the world in authentic lunar science, meeting the goal of the NASA Global Road Map to "Inspire and Educate" and "Create opportunities for participation in space exploration" that will stimulate international engagement in space exploration and development. Phase one of GLEE engaged international student teams through an online workshop where students learned to program and test the LunaSats, and develop their science case for the Lunar phase.

In addition to the large network data collection once on the moon, individual teams code will be activated to collect their desired data. The data will be made available on a public dashboard for future science and analysis, allowing for even greater community science access and opportunity. GLEE is also a Space Grant student run and student designed mission. Students are gaining experience in project management, systems engineering, hardware and software development, and community relations.

Payload Development: The GLEE payload consists of a deployment module, on-board computer and an array of LunaSats. Students have completed the final prototype for the LunaSat for testing and validation, prior to lunar production. The LunaSat is currently being tested utilizing the High Altitude Student Platform (HASP) program, particularly to test the durability of the LunaSat and the robustness of the RF communication system that the mesh network will utilize. The LunaSat Deployment Module is designed for either stationary lander or lunar rover mounting, and will autonomously deploy the chipsat network in a predetermined array pattern. The LunaSat design is optimized for an equatorial deployment. Testing and modeling are underway to determine the viability of a polar region deployment.

GLEE will demonstrate a novel form of distributed data collection - a type of study not possible with current single-instrument missions - inspiring a future generation of space scientists and helping to kickstart the next era of planetary science.

Extraterrestrial Construction: Mesh Decomposition-Driven Collaborative Additive Manufacturing using Robot Swarms for Autonomous Lunar Construction

Marios-Nektarios Stamatopoulos[1] , Avijit Banerjee[1], Matteo Fumagalli[2,1] and George Nikolakopoulos[1], (Contact: marsta@ltu.se)

Introduction: Robotic construction will play a crucial role in the execution of large-scale lunar construction in future missions towards the establishment of accompanying infrastructure. Ensuring adaptability to varying quantities of building materials and the capacity of the robotic fleet is essential for mission versatility and scalability. Unlike conventional methods that rely on large, centralized machinery for sequential and relatively slow construction processes, an alternative approach proposes the utilization of a swarm of smaller-scale robots. This strategy involves decomposing envisioned structures into smaller components, allocated to a robotic fleet for efficient construction [1]. The allocation is executed based on the dependencies and printability of the chunks while prioritizing the parallelization of tasks and minimizing the conflicts between the robots.

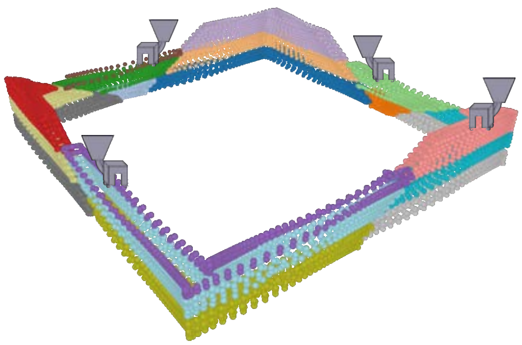

Figure 1: Lunar robots manufacture their envisioned decomposed mesh shown in color-coded chunks.

Mesh Decomposition Procedure: This search algorithm aims to identify an optimal set of planar cuts for segmenting a generic mesh into smaller subparts, referred to as "chunks." The algorithm considers printability constraints specific to the robotic platform, as well as constraints related to the interconnectivity between the chunks, ensuring sufficient overlap between their touching facets. Additionally, the algorithm incorporates metrics to evenly distribute the volume of the initial mesh among the generated chunks, thereby minimizing waiting times between robots and enhancing task parallelization. This is achieved by prioritizing chunks with fewer dependencies compared to others.

Dependency Graph Task Assignment: Each chunk generated by the optimal cut planes search algorithm is treated as an individual printing task assigned to a robot. Task assignment is systematically facilitated by assessing inter-dependencies between chunks and creating a dependency graph illustrating their relationships. Task assignment occurs reactively based on this graph. When a robot becomes available for manufacturing, all manufacturable nodes on the graph are assessed using a combined evaluation metric. This metric prioritizes chunks with more dependent nodes to enhance mission parallelization. Simultaneously, conflict probability between robots traversing manufacturing paths is minimized by calculating each chunk's conflict probability relative to the entire set.

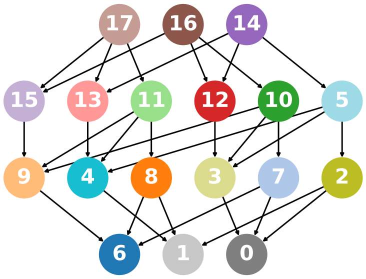

Figure 2: Printing tasks dependecy graph

Robotic Execution: Whenever a chunk is assigned to each robot, it heads towards the start of the manufacturing path and starts the normal manufacturing action by extruding material. All of the robots share their future trajectories in a prediction horizon of a predefined time among them, so that imminent conflicts are detected. The detected conflicts are handled in a decentralized way by dynamically determining one robot suspending its movement until the conflict is resolved.

Conclusion: The shift towards swarms of small-scale robot workers indicates a promising aspect for the autonomous development of infrastructure over the lunar surface. The aforementioned framework, is proposed as a potential mechanism for coordination of the construction process due to its ability to handle a large variety of construction and adapt to the properties of the available equipment at any point.

References: [1] M. Stamatopoulos et al, "Flexible Multi-DoF Aerial 3D Printing Supported with Automated Optimal Chunking", 2023 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS), Detroit, MI, USA, 2023

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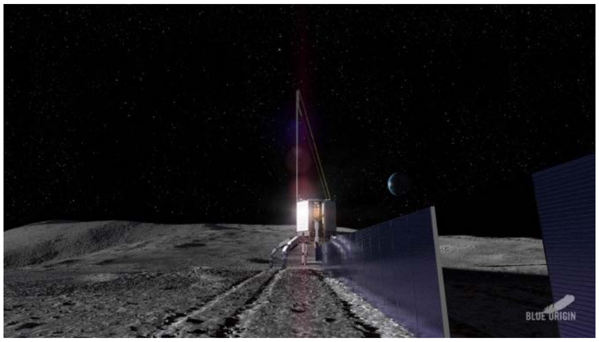
Harnessing Space Resources for the Benefit of Earth at Blue Origin. V. Stamenkovic[1] and Space Resources Program Team, [1] Space Resources Program, Space Systems Development, Blue Origin. (Contact: VStamenkovic@blueorigin.com)

Introduction: Blue Origin was founded with a vision of millions of people living and working in space for the benefit of Earth. Blue Origin envisions a time when people can tap into the limitless resources of space and enable the movement of damaging industries into space to preserve Earth, humanity's blue origin. Blue Origin is working today to create that future by developing reusable launch vehicles and in-space systems that are safe, low cost, and serve the needs of all civil, commercial, and defense customers. Blue Origin's efforts include flying astronauts to space on New Shepard, producing reusable liquid rocket engines, developing an orbital launch vehicle with New Glenn, and returning to the surface of the Moon in a more permanent way. These endeavors will add new chapters to the history of spaceflight and move all of humanity closer to that founding vision.

A key part of this vision is the harnessing of space resources for the benefit of Earth. The Space Resources Program within Space Systems Development at Blue Origin has been established to address the challenges required for opening space resources to humanity and to use them in-situ, starting with the Moon.

The Space Resources Program at Blue Origin was ignited in 2020 and consists today of scientists and engineers across various disciplines from geophysics, geochemistry, geology, instruments, materials, chemistry, production, and all engineering disciplines required to design, build, and maintain resource prospecting, processing, and manufacturing systems in space – primarily focusing on developing the Blue Alchemist system.

The core technology for the Space Resources Program is Blue Alchemist [1], an end-to-end, scalable, autonomous, and commercial solution that produces solar cells, wire, and oxygen from lunar regolith. Based on a process called molten regolith electrolysis, the breakthrough will bootstrap unlimited electricity and power transmission cables anywhere on the surface of the Moon.



In this talk, I will provide an overview of our Space Resources Program and our Blue Alchemist core technology development in partnership with NASA through a Tipping Point award [2] and expand on how this technology will support a vivid lunar economy in this decade.

References:

[1] https://www.blueorigin.com/news/blue-alchemist-powers-our-lunar-future

[2] https://www.blueorigin.com/news/blue-origin-awarded-nasa-partnership-to-turn-lunar-regolith-into-solar-power-systems-on-the-moon

TRUSSES: Temporarily, Robots Unite to Surmount Sandy Entrapments, then Separate.

Douglas Jerolmack[1], Daniel Koditschek[1], Feifei Qian[2], Mark Yim[1], Cynthia Sung[1]*, [1]University of Pennsylvania, [2]Unviersity of Southern California. (*Contact: crsung@seas.upenn.edu)

Introduction: Future exploration of lunar environments will require the ability to identify, negotiate, and recover from hazards such as sinkage into the terrain, slipping on slopes, large boulders or crevices. Our project aims to investigate how heterogeneous teams of robots can jointly overcome environmental hazards in sandy terrain by attaching to each other to form larger and more stable, maneuverable structures. The overall project concept is shown in Figure 1. As a team of rovers traverses an environment, they use their interactions with the ground to estimate ground properties, build models of robot-to-regolith interactions, and form a map of safe and risky terrain. When ground traversal risk is high, robots attach to each other using rigid extendable prismatic arms, forming 2D and 2.5D trusses that allow them to apply forces to each other and thus to compensate for unfavorable ground conditions. Similar maneuvers can also be used to rescue robots that have become entrapped.

In first steps towards the development of this system, we investigate: (1) strategies for estimating ground properties through robot locomotion and (2) strategies for robots to connect and move as a truss structure.

High-Mobility Regolith Sensing: For rovers moving through an environment, direct surface interactions can be used to collect rich information about the terrain opportunistically (i.e., without having to stop to collect sensing information). We currently focus on legged platforms, which have demonstrated the ability to traverse a wide range of natural terrains, including loose regolith with different levels of compaction [1]. Our initial studies involve comparisons between data collected by static robot legs acting as force probes and data collected on-the-fly via walking. Preliminary results show significant differences in normal stress measured in loose regolith as compared to crusty ripples [2] in both modes, although measurement uncertainty is higher for a moving platform due to changes in motor friction and robot pose.

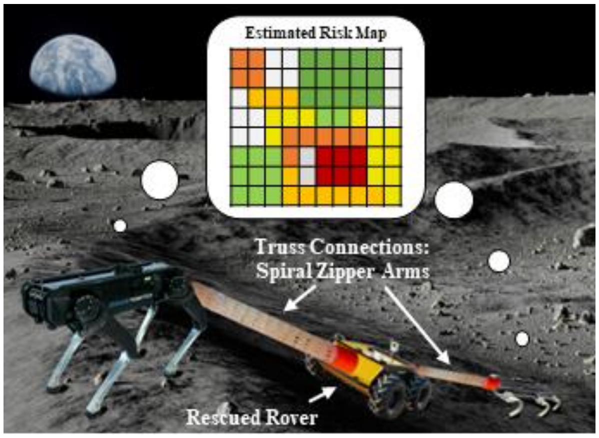


Figure 1. Project concept. Heterogeneous teams of robots connect into trusses to assist each other in traversing challenging terrain.

Multi-Agent Truss Formation and Planning: When escaping or avoiding hazards, multiple robots connected together provide more degrees of freedom, which can be used to apply forces in otherwise impossible ways. Our proposed strategy builds on the Spiral Zipper Arm [3], a single band of material that joins together to form a stiff cylindrical column. Our initial design has demonstrated extension ratios of up to 10:1 and load-bearing capabilities up to 200N for a single arm. Arms connecting robots into a truss can also coordinate to apply forces non-axially to any of the contributing members. Preliminary work has shown how extending arms in a truss formation are able to manipulate the relative positions of the nodes using gradient-descent based planners [4].

Ongoing Efforts: Our initial explorations demonstrate feasibility of coordinated robot exploration and locomotion, and our current efforts aim to refine results in each of our two focus areas. We are analyzing regolith sensing data to identify trends in how both the measured force response and estimation uncertainty change over different regolith compositions, as well as building a larger library of locomotion behaviors for sensing. We are also working to incorporate regolith models into our reconfiguration planners so that robots in both separated and connected truss forms can predict the result of leg or arm motions.

Acknowledgements: This work was supported by Lunar Surface Technology Research grant #80NSSC24K0127 from NASA's Space Technology Research Grants Program.

References: [1] F. Qian et al. (2017) *Aeolian research, 27,* 1-11. [2] E. Fulcher et al. (2024) *LPSC* (under review). [3] A. Spinos et al. (2017) *IROS,* 2717-2722. [4] S. Misra et al. (2022) *ICRA,* 3238-3244.

Deep Vac Fantastic: A Method of Rapid Acquisition of Lunar Regolith.

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Introduction: In Situ Resource Utilization (ISRU) of lunar regolith has been proposed for a number of construction and development tasks needed to achieve lunar permanence. Many of these proposals rely on rovers to gather material from the surface and bring it back to a lander or hab, and bucket arms to load material into a processing structure. This architecture has significant terrestrial heritage but collection of sufficient quantities of material may take a large portion of the approximately two week long lunar day. This is important for any ISRU technologies that are needed for lunar night survival such as thermal systems or barriers, or life sustainment systems like oxygen production. We propose a new system, leveraging high TRL Honeybee Robotics lunar technologies, for rapidly acquiring large volumes of lunar regolith.

Deep Vac Fantastic (DFV) uses a pneumatic downhole system to rapidly excavate a borehole and collect all of the contents into a storage area on the lander (Figure 1). This tool is primarily a combination of three Honeybee flight developments; Lunar PlanetVac [1], DIABLO (Deployable Interlocking Actuated Band for Linear Operations), and LISTER (Lunar Instrumentaion for Subsurface Thermal Exploration with Rapidity) [2], along with pneumatic dirty flow technologies developed for the Pneumatic Transport System on the Dragonfly mission to Titan.

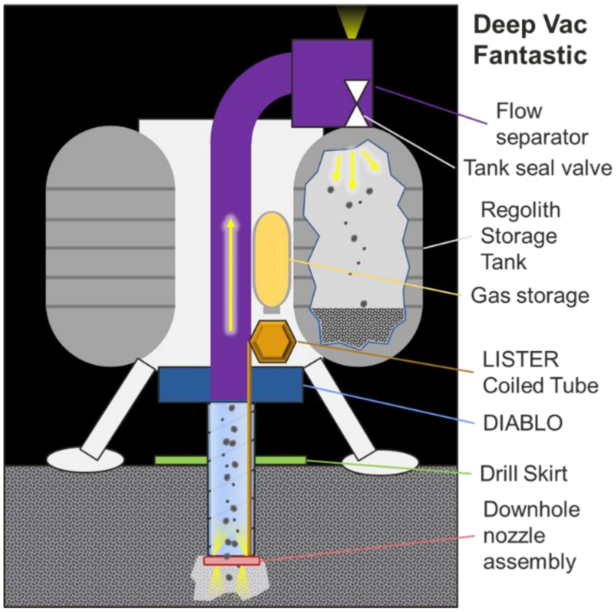

Figure 1. A diagram of Deep Vac Fantastic

The downhole nozzle assembly will take the lessons learned from Lunar PlanetVac and the Pneumatic Sampler developed for JAXA's MMX mission to Phobos to orient gas nozzles to both excavate material and direct regolith up to a collection tank. Depending on the size of the borehole, pressure used, location on the lander, and mass of the lander, a gas nozzle may also be needed at the top of the lander to provide downward force to keep the lander balanced and grounded, as was done on MMX. Gasses exiting through the flow separator will also provide balancing forces. A drill skirt is needed during initial drilling to ensure that gas and regolith travel up through the system instead of out along the surface.

Figure 2. LISTER pneumatic drilling excavates a borehole of ~100 mm diameter to 3 m depth (right and center) DVF aims to capture these cuttings using the mast technology employed in LAMPS (right)

The downhole nozzle assembly is fed into the ground using the DIABLO mechanism being used in Honeybee's LAMPS (Lunar Array Mast and Power System) development, while the pneumatic line is fed using the LISTER coiled tube deployer. Both instruments can be readily altered to accommodate various depths and bore diamters. A trade between pneumatic force at drill area and capable drill depth is needed. For example, a 6" bore needs to drill 14 m to collect 1 m^3 (min 1100 kg depending on regolith density) of material, where for the same volume an 8" bore only drills 8 m.

References: [1] Zacny, et al. "PlanetVac: pneumatic regolith sampling system." 2014 IEEE Aerospace Confer-ence. IEEE (2014) [2] Ngo, P., et al. "Engineering and Test Development of Heat Flow Probe and Pneumatic Drill for Lunar Lander Mission to Mare Crisium." 53rd Lunar and Planetary Science Conference. Vol. 2678. 2022.

An Integrated Architecture Study for Autonomous Lunar Construction.

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Lunar construction is an expanding field within NASA's Moon to Mars goals and objectives that presents many challenges and requires innovative and reliable forms of autonomous construction on the surface of the Moon to further the technologies needed for human space exploration. Marshal Space Flight Center's (MSFC) Advanced Concepts Office (ACO) addressed Lunar Infrastructure Objective LI-4[i] by developing a Pre-Phase A, integrated architecture to inform a demo for lunar construction operations. The ACO study traded three architectures that would survey and prepare a construction area to build a landing pad out of lunar regolith using MMPACT (Moon-to-Mars Planetary Autonomous Construction Technology) platforms, rovers, and navigation outposts. The main trades examined navigation for the system/architecture, options for rover navigation, battery vs continuous tether power for the MMPACT robotic arm, and assigning site prep functionality to the rovers vs the platforms. Results of the study determined that the best options for the scenario provided would be local navigation (more accurate and continuous), a combination of Light Detection and Ranging (LiDAR) for initial site mapping with subsequent Smart Video Guidance Sensors (SVGS) to save power for construction, and using tethered power to decrease mission duration. The team also concluded that assigning site prep functionality to either the rovers or the platforms has benefits and challenges; future studies could explore having that functionality on both the rovers and platforms. Lastly, the team provided a detailed Concept of Operations (ConOps) that could be used in real-time ground demonstrations to explore the mission timeline, construction processes, autonomous operations, and communication systems that can be tested using MSFC's lunar regolith field and Lunar Utilization Control Area (LUCA) capabilities.

Leveraging Commercial Flight Tests to Advance Lunar Technologies. G. H. Peters,[1] J. A. Zimo,[2] E. W. DiVito,[1] and C. E. Tuck[1], [1]Armstrong Flight Research Center, Edwards, CA 93523, [2]NASA Headquarters, 300 Hidden Figures Way SW, Washington, D.C. (Contact: chloe.e.tuck@nasa.gov)

Introduction: NASA's Flight Opportunities program leverages commercial flight providers to accelerate the maturation of space technologies using suborbital rocket-powered vehicles, aircraft flying parabolic trajectories, and high-altitude balloons, as well as orbital platforms that can host payloads in cooperation with NASA's Small Spacecraft Technology program. Cost-effective and timely access to relevant space environments can help advance technology readiness levels (TRLs) and reduce risk ahead of longer, more expensive missions, including missions to the Moon and Mars.

Since 2011, Flight Opportunities has supported over 280 flights with more than 918 tests of payloads. These flight tests have supported the maturation of technologies and research with applications for lunar exploration and the development of resilient lunar infrastructure.

Lunar Technology Testing and Infusion Highlights: Presenters will provide examples of lunar technologies that can benefit from flight testing, including entry, descent, and landing systems; dust mitigation techniques and tools; in situ resource utilization approaches; on-demand manufacturing of electronics; and small spacecraft sensing and communications technologies.

Representatives will also highlight lunar technologies previously tested through the program that have been infused into other missions, including several that are slated for NASA Commercial Lunar Payload Services (CLPS) program demonstrations. For example, two technologies aboard the Intuitive Machines Nova-C lander that touched down on the Moon on Feb. 22, 2024 were advanced through Flight Opportunities. NASA Langely's Navigation Doppler Lidar (NDL) and NASA Glenn's Radio Frequency Mass Gauge (RFMG) were both matured through suborbital flight tests, and went on to play important operational roles during the mission.

Presenters will also discuss the capabilities offered by industry flight providers that work with the Flight Opportunities program. A number of these commercial providers offer vehicles uniquely suited to testing technologies ahead of lunar missions, including:

- Aircraft from Zero Gravity Corporation that fly parabolic trajectories, creating lunar, Martian, and microgravity
- Blue Origin's New Shepard rocket with capabilities for both lunar gravity and microgravity
- Platforms that can host payloads in orbit – such as orbital maneuvering vehicles, small spacecraft, and launch vehicle stages – providing extended periods of microgravity

Leveraging Flight Test Expertise and Access to Commercial Flight Providers: There are a variety of ways for organizations and researchers to engage with the Flight Opportunities program. Non-government researchers can propose for payload development and flight test funding through the program's solicitations and challenges, including the NASA TechFlights solicitation and the NASA TechLeap Prize. Researchers currently supported by NASA or another government organization can work with the program directly for additional options to access commercial flight tests.

Flight Opportunities can also collaborate with offices and teams within NASA and other government agencies to offer access to flight tests with commercial flight providers. Presenters will highlight examples of successful collaborations in which the program has partnered with key stakeholders to advance solutions that address a critical technology gap. These collaborations offer several advantages, including access to Flight Opportunities team members with flight test subject matter expertise and support for flight provider engagement through exisiting commercial contracts.

Get Involved: Flight Opportunities presenters will highlight the resources available to researchers interested in engaging with the program, including:

- Monthly Community of Practice webinar series
- Monthly Flight Opportunities newsletter
- Opportunities for one-on-ones with program team
- Online flight test lessons learned library
- Online portfolio of previously tested technologies

EAT: Environment Agnostic Traversability for Reactive Navigation. Mario Alberto Valdes Saucedo[1], Akash Patel[1], Avijit Banerjee[1], Christoforos Kanellakis[1] and George Nikolakopoulos[1], [1]Robotics and Artificial Intelligence Group, Department of Computer, Electrical and Space Engineering, LuleåUniversity of Technology (Contact: marval@ltu.se)

Introduction: It is a common practice to rely on geometric features of the environment for the task of navigation, where in most cases the registered geometric information does not take into consideration other properties on the local surroundings (e.g. type of surface or type of obstacles). Nevertheless, in the case of unstructured environments, the task of navigation can be particularly challenging, due to the presence of complex scenarios, where the geometric features of the environment might not be enough to determine safe traversable routes. Some of the challenges that arise for geometric based navigation is the presence of see-through obstacles like ice, or unfavorable surfaces like water or sand, that may be flat but undesirable or in some cases untraversable for the respective robotic platform. The presence of these unique hazards brings forward the need for the robotic platform to understand its environment in a higher level. For such task is common to use the notion of traversability, which allows to understand the environment in function of the semantics of the terrain and the surrounding obstacles.

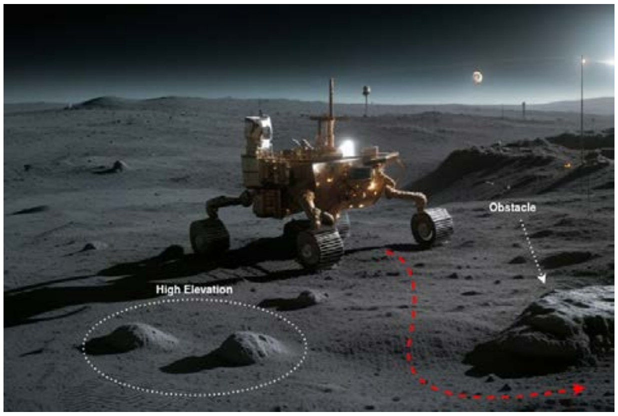


Figure 1: Depiction of the proposed concept

Terrain Segmentation: We relied in a semantic segmentation model in order to estimate the semantic class label of the roughness level for the terrain present on the environment, which consists of 6 classes: *Background*, Information that is least relevant for the navigation (e.g. sky). *Obstacle*, All terrain types that are considered untraversable, like rock-walls. *Risky*, The least traversable terrain, mainly due to its dangerous nature, like is the case of water or ice. *Rough*, Terrain that is traversable but undesirable in contrast to better alternatives. Some examples are gravel and sand. *Coarse*, Terrain that is traversable but is not always meant to be traversed. Lose dirt will be the most common one. *Flat*, Optimal terrain to be traversed by the robotic systems (e.g. solid-rock floor).

Surface Normals: In addition, the geometric features of the environment are extracted using the surface normals estimated from depth images.

Traversability Decay Function: The definition of traversability relies on the robotic platform, in the case of mobile robots, can be seen as a function depending on the terrain and the geometric properties of the same. This under the understanding that is better to traverse an solid-rock path rather than a gravel path. In a similar way, high slopes are considered less desirable than flat surfaces even if both are made of solid-rock. While is possible to represent traversability like a boolean function (e.g. the terrain is either traversable or untraversable), when it comes to unstructured environments like is the case of space environments and subterranean environments, the definition of traversability like a boolean or even a discrete function can be restrictive. With that in consideration, we propose the following traversability decay function: $\boldsymbol{t}(\alpha,\ \theta) = \alpha\,\text{exp}^{-\frac{\theta}{\alpha}}$ where α is the terrain label and θ is the slope estimated from the surface normals. The function behaves so that based on the terrain class the traversability decays faster in function of the slope. Retaking the previous example, dirt becomes non-traversable at less steeped slopes than solid-rock. In addition, the maximum traversability value that the function can take depends on the terrain class. Since even if both, dirt and solid-rock, are perfectly flat, the solid-rock is still a most desirable terrain to traverse.

Conclusion: The proposed method works by fusing semantic information obtained from RGB images with geometric information of surface normals, extracted from depth images, using the proposed novel traversability decay function to obtain a traversability density image. The resulting images are more intuitive less environment-reliant representation of the traversability of the scene, allowing the robotic system to adapt to terrains that were not present in the training. This property allows the framework to work in novel an unknow terrains, an occurrence common in lunar exploration.

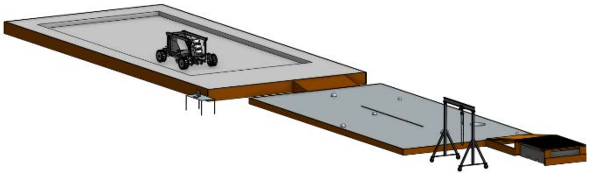
References: [1] M. A. V. Saucedo, A. Patel, C. Kanellakis, and G. Nikolakopoulos, “EAT: Environment Agnostic Traversability for reactive navigation,” Expert Systems with Applications, vol. 244, p. 122919, 2024, doi: https://doi.org/10.1016/j.eswa.2023.122919.

Field Testing Experience of Lunar ISRU technology. P.J. van Susante[1], [1]Michigan Technological University, 1400 Townsend Dr. Houghton, MI 49931 (Contact: pjvansus@mtu.edu)

Introduction: The start of the CLPS landings with Astrobotic's attempt and Intuitive Machines almost successful landing on the lunar surface in the past few months, and the coming lunar activities for permanent lunar presence means that ever more surface technologies are in need for higher TRL testing. Given the limited access to and the limited size of dusty thermal vacuum chambers (DTVAC), tests will have to be performed in testbeds filled with lunar simulant indoors or sometimes outdoors due to size requirements. No lunar proving ground facility or consortium exists yet to support such testing. To test our ISRU technology, the Michigan Technological University's Planetary Surface Technology Development Lab (PSTDL) has created several testbeds, indoors and outdoors. This talk will discuss the experience and lessons learned of creating temporary large scale lunar outdoor test beds using 10-30 mt of (icy) regolith simulant.

Outdoor Testbeds Needs:

For the Break the Ice Lunar Challenge 15 day Durability Demonstration Test, a 13.25m x 6m x 0.4m weak concrete slab was poured with a compressive strength of 1.5-2 MPa and a 10m x 5m x 0.2m drive area filled with 16,000 kg of lunar simulant was made. For weather protection, large tents without center posts covered the excavation and drive areas and smaller tents covered the transition zone, deposition zone and control station. The goal was to excavate 800kg/day for a total of 12,000kg in 15 days, drive 500m on the lunar simulant for every trip from excavation site to dump site.



For the LuSTR20 icy regolith trench testing a 7m x 1.5m x 1.2m trench filled in two zones with layers varying from dry, 3wt%, 6wt% and 9wt% icy regolith simulant was created. The goal was to test the percussive heated cone penetrometer to determine geotechnical properties down to 1m and to determine volatile content every 10 cm.

Experience: Building the temporary large size test beds poses many logistical challenges.

- Storing, drying, freezing, mixing, depositing 15-25 mt of (icy) lunar simulant
- PPE is required when working with and disturbing the lunar simulant.
- Creating stable desired conditions (dry, frozen, layers, ice content, compaction level)
- Timing and dealing with weather (snow, rain, thunderstorm, high winds can all cause dangerous situations or disturb the site, damage equipment etc.)
- Test equipment needs to be weather proof
- Working shifts through the night requires careful planning and logistics

Lessons Learned: Many lessons were learned, many of which stress the need for a lunar proving ground facility/consortium:

- Weather and moisture greatly affect the lunar regolith simulant behavior and sensor results and the desired test conditions are hard to control, it also requires additional measures to make sure computers and other equipment does not freeze or gets wet.
- Icy regolith creation at large scale (1-10 metric tons) and drying it before and after testing as well as storing it dry before and afterwards is time, space and resource consuming.
- PPE in winter conditions has additional challenges with fogging up and getting wet.
- Despite challenges, valuable data was gathered of full scale integrated operating systems about control and feedback, software, performance, wear, excavation, storage and transfer of regolith, ability to drive 3000 times over the same regolith, collecting GPR data as well as geotechnical and thermal volatile data. We are now processing several GB of data.
- It would be better to do this kind of testing in a controlled indoor environment at full scale, which would yield more accurate lunar conditions and data. This illustrates the need for a lunar proving ground facility as discussed in previous LSIC meetings, so investments in creating these temporary test beds does not go to waste.

VORA: Vision for OffRoad Autonomy.

Juan Luis Vasquez[1], Harold A. Garza[2], Meera Day Towler[3], [1]Southwest Research Institute (SwRI), c/o Juan Luis Vasquez (B68) 9503 W Commerce St. San Antonio TX 78227, [2]SwRI, c/o Abe Garza (B68) 9503 W Commerce St. San Antonio TX 78227, [3]SwRI, c/o Meera Towler (B68) 9503 W Commerce St. San Antonio TX 78227. (Contact: juanluis.vasqueznavarrete@swri.org)

In offroad autonomy, there are many challenges for perception systems that solely rely on vision-only sensors. Presented here is research into a vision-based system featuring algorithms and software with stereo cameras to perceive objects, to model environments, and to simultaneously localize and map while driving offroad.

SwRI's VORA research project used passive, vision-only sensors to generate a dense, robust world model for use in offroad navigation. This research focused on generating vision-based autonomy algorithms applicable to defense and surveillance autonomy and planetary exploration. Passive perception for traversability estimation allows for less power requirements and does not require expensive/specialized sensors (e.g., radar or lidar), which makes it an appealing option for defense and space.

SwRI researched three technical approaches for achieving dense, robust world modeling for offroad navigation. These included Deep Learning Stereo Matching (DLSM), improved visual odometry using factor graph optimization, and a ground segmentation algorithm capable of effectively incorporating dense depth data. Ultimately, these three components were fed into SwRI's existing traversability estimation software to produce highly accurate navigation costmaps. Testing was performed on a SwRI-owned HMMWV 1165 at SwRI's campus and in a high-fidelity modeling and simulation environment.

With notable improvements, DLSM was successfully developed and provided dense depth information beyond what typical stereo matching algorithms can provide. Figure 1 shows the dense and accurate disparity map from DLSM. The results from the classical technique lost a tremendous amount of detail in the outermost edges of the image, which reduced confidence in the disparity map as a whole and required multiple stereo images from various perspectives of the same scene to provide the same data DLSM provides in a single view.

SwRI implemented factor graph optimization from the data of two different sensing modalities—stereo cameras and an Inertial Measurement Unit (IMU)—and incorporated it into the Visual Simultaneous Localization and Mapping (VSLAM) pipeline. Visual odometry was used for the stereo cameras and paired with data from the IMU, creating a common framework that allowed highly accurate pose estimations over long periods of time (Figure 2).

The ground segmentation algorithm incorporated the 3D geometry of the environment and semantic segmentation, significantly improving a geometric based approach to segmentation.

The completed research from this effort has been integrated into a coherent perception pipeline and world model for SwRI's offroad autonomy stack. The results will lessen or eliminate SwRI's lidar dependency, which will position SwRI to meet the growing need for passive perception in space and defense applications.

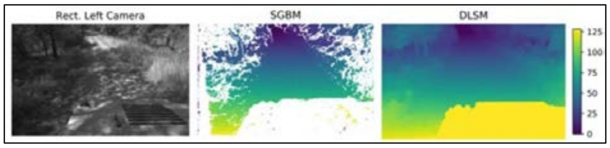


Figure 1. Comparing classical stereo matching performance against DLSM. From left to right: original left monochrome image; classical stereo matching disparity map; DLSM disparity map.

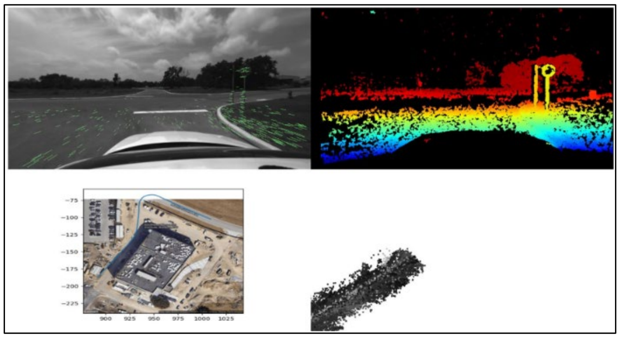


Figure 2. VSLAM Using Factor Graph Optimization. Keypoint Detection/Matching with subsequent frames (top left); classical stereo matching disparity map generated from the left/right camera pair (top right); estimated path around one building at SwRI headquarters (bottom left); sparse volumetric point cloud being generated by VSLAM via triangulation and the sparse disparity (bottom right).

Lunar Regolith Glass Frames for Repurposable Structural Voxels.

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Introduction: Physical Sciences Inc. (PSI), in support of its broader research into lunar *in situ* resource utilization (ISRU), is developing methods for molding mass-efficient structural components from lunar regolith simulant glass (melted simulant powder reformed into glass). The current effort is focused on the production of identical frame parts that couple together into a 6-sided voxel as illustrated in Figure 1. This emulates the concept developed under the NASA Automated Reconfigurable Mission Adaptive Digital Assembly Systems (ARMADAS) project.[1] PSI is developing its process methods and part specifications in collaboration with the NASA ARMADAS team to strategize potential pathways for automated bulk production, lunar applications, and eventual lunar implementation.

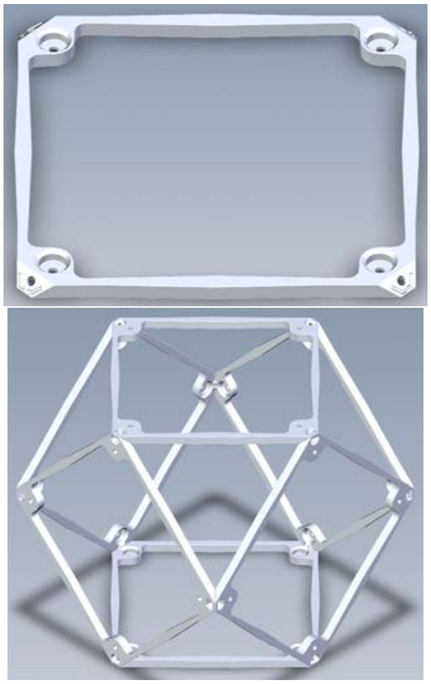

Figure 1. Initial CAD design of regolith glass frame part (top) and assembled voxel (bottom).

Prior work: This research thrust into regolith glass structures began with the DARPA Novel Orbital Moon Manufacturing, Materials, and Mass-Efficient Design (NOM4D) for precise fabrication of large aperture space structures. In this project PSI demonstrated exquisite rod-truss struts made of welded regolith silumant glass rods and cast glass nodes for connecting the struts together.[2] Subsequent exploration focused on the production of plates and frames and the addition of fine features and cuts in post-processing. Figure 2 illustrates the molding of a simple frame in process and a molded plate that was cut with a water jet process.

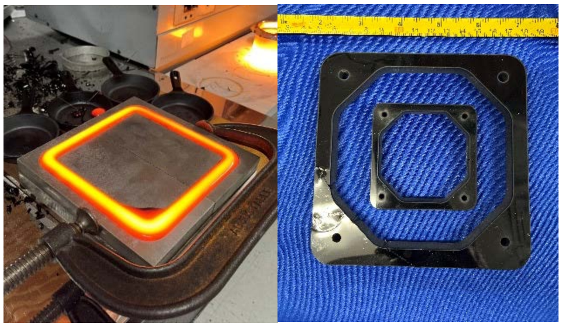

Figure 2. (left) Hot regolith simulant glass in an open frame mold. (right) Regolith simulant glass tile cut with water jet.

Current project: The current effort underway at PSI is aimed at optimizing all of the part design, press-mold design, and part fabrication process to yield consistent and healthy parts. Developed processes aim to avoid real-time and residual material stresses (which can compromise part strength), while the part specifications aim for a 14cm square frame that balances strength against mass (target material volume = 25cm^3). The overarching objective is to demonstrate a process that: 1) yields a consistent product that meets specifications; and 2) has a devised path forward for higher-volume production with simplest (and lunar compatible) steps. Produced parts are to be tested for tensile modulus, tensile strength, and dimensional accuracy/consistency.

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[1] Cheung, K., Gregg, C., and Taylor, E. (2022) *LSIC Spring Meeting* presentation.

[2] Nunan B. E., Corbin, J., Arzt, Z. A., Seymour, J. M., Wainner, R. T., Hessel, C. M., Warren, P. A., and Stern, M. (2024) *AIAA Scitech Conference* paper 2024-0824.