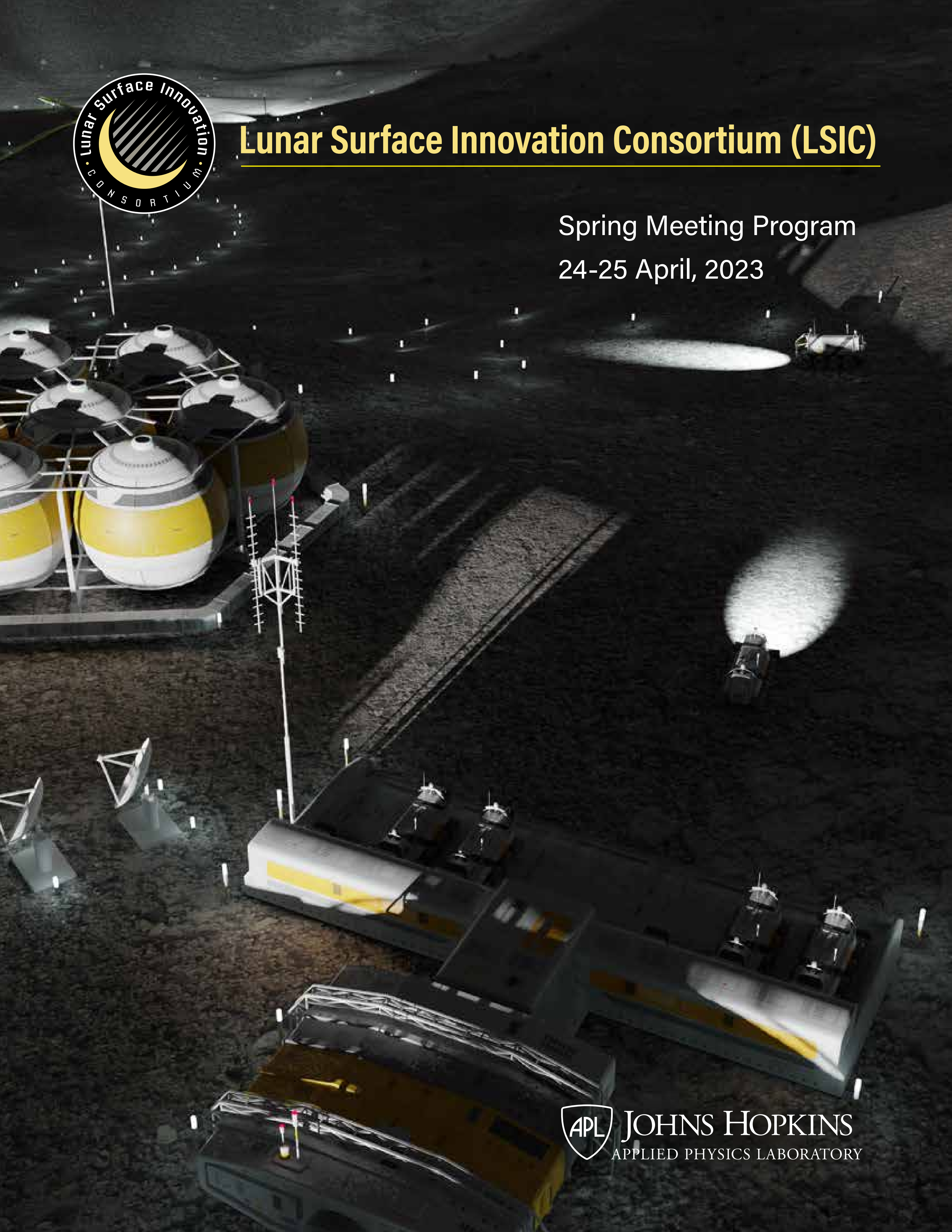
Lunar Surface Innovation Consortium (LSIC)

Spring Meeting Program

24-25 April, 2023



JOHNS HOPKINS
APPLIED PHYSICS LABORATORY

Technical Organizing Committee

Jodi Berdis, JHU Applied Physics Laboratory
Athonu Chatterjee, JHU Applied Physics Laboratory
Alice Cocoros, JHU Applied Physics Laboratory
Miguel Coto, Colorado School of Mines
Stephen Daire, Protean Industries
Roberto de Moraes, Aecom
Erik Franks, Cislune
Karl Hibbitts, JHU Applied Physics Laboratory
Kristin Jaburek, JHU Applied Physics Laboratory
Ian Jakupca, NASA
Haleigh Kling, Lunasonde
Michael Nord, JHU Applied Physics Laboratory
Mark Perry, JHU Applied Physics Laboratory
Samalis Santini De Leon, JHU Applied Physics Laboratory
Lindsey Tolis, JHU Applied Physics Laboratory
Paul van Susante, Michigan Technological University
Bo Varga, WBGlobalSem
Sarah Withee, JHU Applied Physics Laboratory
Sean Young, JHU 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 under the Lunar Surface Innovation Initiative. LSIC fosters communications and collaborations among academia, industry, and Government. Members have expertise in LSII key capability areas.

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

Lunar Surface Innovation Consortium (LSIC)
Spring Meeting Draft Agenda
All times Eastern
April 24th- 25th, 2023

Day 1 – Monday, April 24th, 2023

9:00	*Coffee & Networking in Person and in GatherTown – FG Mingling Areas*	
10:30	In-Person Welcome and Logistics	**Rachel Klima**, LSIC Director **Robert Braun**, Sector Head, Space Exploration Johns Hopkins Applied Physics Laboratory (APL)
10:35	NASA's Blueprint Objectives	**Kurt "Spuds" Vogel**, Director of Space Architecture, NASA
11:00	NASA Space Tech Update	**Jim Reuter**, Associate Administrator for Space Technology, NASA
11:25	**Fireside Chat**	**Moderator: Niki Werkheiser**, NASA
	Kurt "Spuds" Vogel, Director of Space Architecture, NASA	
	Jim Reuter, Associate Administrator for Space Technology, NASA	
11:50	*Break*	
12:10	LSII and LSIC Updates	**Wesley Fuhrman**, APL LSII Lead **Rachel Klima**, LSIC Director **LSII Team** Johns Hopkins Applied Physics Laboratory (APL)
13:00	*Lunch Break and LSIC Community White Paper Discussions*	
14:40	**Panel:** LuSTR Project Results	**Moderator: Harri Vanhalla,** NASA
	Paul van Susante, Michigan Technicological University (ISRU)	
	Ahsan Choudhuri, University of Texas at El Paso (ISRU)	
	Phillip Lubin University of California, Santa Barbara (Power)	
16:00	*Break*	
16:20	Lightning Talks	
17:00	Poster Session and Networking	
18:00	*Adjourn for the Day*	

Lunar Surface Innovation Consortium (LSIC)
Spring Meeting Draft Agenda
All times Eastern
April 24th-25th, 2021

Day 2 – Tuesday, April 25th, 2023

9:00	*Coffee & Networking in Person and in GatherTown – FG Mingling Areas*	
10:30	Welcome and Introduction	**Robert Braun**, Sector Head, Space Exploration Johns Hopkins Applied Physics Laboratory (APL)
10:35	**Panel:** Government Collaboration To Meet Long-term Goals for a Lunar Ecosystem	**Moderator: Walt Engelund**, NASA
10:35	NASA Perspective	**Pam Melroy**, Deputy Administrator, NASA
10:55	DARPA Perspective	**Stefanie Tompkins**, Director, DARPA
11:05	OSTP Perspective	**Matt Daniels,** Assistant Director for Space Security and Special Projects, White House OSTP
11:20	Panel Discussion	**All Previous Speakers** **Kurt “Spuds” Vogel**, Director of Space Architecture, NASA
12:00	*Break*	
12:20	CLPS Program Updates	**Brad Bailey,** NASA
12:40	**Panel:** CLPS Program	**Moderator:** Joshua Cahill, APL
	Michael Provenzano, Director, Lunar Surface Systems, Astrobotic	
	Benjamin Bussey, Chief Scientist, Intuitive Machines	
	Michael Sims, CEO and Founder, Ceres Robotics	
	Alan Campbell, Senior Program Manager, Draper	
	Israel Figueroa, Director, Systems Architect and Solutions, Firefly Aerospace	
13:10	*Lunch Break and Small Group Discussions: National Stategy*	
14:40	**Panel:** How do Long-term Use Cases Drive Technology Development	**Moderator:** Wes Fuhrman, APL
	Carla Haroz, Antarctic Operations Manager, National Science Foundation	
	Kristina Gibbs, SSERVI Deputy Director, NASA	
	Timothy Cichan, Space Exploration Architect, Lockheed Martin	
	Kristen John, Technical Integration Manager for Lunar Dust Mitigation, NASA	
	James Mastandrea, LSIC Interoperability Working Group Lead, JHUAPL	
	Shatel Bhakta, Lunar Architecture, NASA	
15:40	*Break*	
16:00	**Group Discussion** – Findings and Recommendations	
17:00	*Adjourn Meeting*	

Speakers

Bill Bailey

Assistant Deputy Associate Administrator for Exploration, NASA

Dr. Brad Bailey has been with NASA for 16 years, the last 4 of which have been at NASA HQ as a program scientist and then as the Assistant Deputy Associate Administrator for Exploration (ADAAX) within the Science Mission Directorate. Prior to that, Brad worked at NASA Ames as first the staff scientist and then the deputy director of the Solar System Exploration Research Virtual Institute (SSERVI) as well as the deputy director for Management and Development at the NASA Astrobiology Institute. During his time at NASA Headquarters, Brad has represented SMD at the Agency level in several areas including serving on major acquisition SEBs, 9th floor study teams, and as co-chair/SMD lead of several multi-directorate working groups (e.g. Utilization, Integration, and Coordination Group (UCIG), Cross-Artemis Site Selection Analysis team (CASSA), CLPS Manifest Selection Board). Brad has additionally taken on directorate responsibilities in establishing a new funding line for lunar instruments for delivery via CLPS and Artemis, as well as coordinating science efforts across STMD, ESDMD, SOMD, and SMD. In his integration role, Brad has also taken the lead on CLPS payload collaborations with our international partners and acts as the co-chair of the International Space Exploration Coordination Group (ISECG) Science Working Group (SWG).

Shatel Bhakta

Agency Lunar Architecture Team Lead, NASA

Shatel Bhakta (seh-thul bhuck-tha) is the lead architect for the Lunar Architecture Team (LAT) for NASA's Artemis Enterprise. He leads this multidisciplinary team across NASA centers in the development of the Lunar Architecture and Artemis Base Camp, and their associated mission planning, concept of operations, site planning, trades and analysis, system element conceptualization, and system-of-systems integration.

Shatel earned his undergraduate degree in Mechanical Engineering from The University of Texas at Austin and his graduate degree in Space Architecture from the University of Houston. He has over 20 years of experience in human spaceflight program development and operations ranging from ISS, Orion, to Gateway.

Robert Braun

Space Exploration Sector Head, Johns Hopkins APL

Dr. Robert D. Braun serves as Head of the Space Exploration Sector at the Johns Hopkins Applied Physics Laboratory since March 14, 2022. As sector head, Dr. Braun is responsible for the accountability and performance of the Sector as an enterprise, developing and executing a sector strategy, and representing the Laboratory to the sponsor communities. He oversees the activities of the Civil Space and National Security Space Mission Areas and the 1300 team members who support the sector's efforts. Dr. Braun earned a Bachelor of Science degree in aerospace engineering from Penn State University, a Master of Science degree in astronautics from George Washington University, and a Ph.D. degree in aeronautics and astronautics from Stanford University. Dr. Braun is a member of the National Academy of Engineering, a Fellow of the AIAA and AAS, and the author or co-author of over 300 technical publications. He has more than 35 years of experience as a space systems engineer, technologist, and organizational leader.

Speakers

Ben Bussey

Chief Scientist, 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 recently joining Intuitive Machines. 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.

Josh Cahill

Deputy Director, LSIC
Senior Staff Scientist, JHU Applied Physics Laboratory

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

Speakers

Alan Campbell

Senior Program Manager, Space Systems

Alan Campbell has more than a decade of experience in the aerospace industry in numerous technical, managerial, and leadership roles. Alan joined the Space Systems Program Office in 2018 to lead the Draper Commercial Lunar Payload Services (CLPS) team which was recently selected to land three NASA-funded science payloads on the far side of the Moon, extending Draper's pioneering lunar heritage dating back to the development of the Apollo Guidance Computer. He is responsible for leading business development, capture, and program execution activities focused on civil and commercial (cis-)lunar architecture opportunities including NASA crewed and autonomous lunar programs such as CLPS and Human Lander System (HLS). Alan continues to lead Draper's work on HLS as part of the Blue Origin-led National Team.

Prior to joining Draper, Alan completed a Master of Science in Engineering degree in Aerospace Engineering and Engineering Mechanics from the University of Texas at Austin specializing in Orbital Mechanics and Controls with a focus on spacecraft trajectory optimization. Alan received his Bachelor of Science degree in Aerospace Engineering from the Schreyer Honors College at Penn State University.

Dr. Ahsan Choudhuri

Associate Vice President, Aerospace Center, Professor of Mechanical Engineering, University of Texas at El Paso

Dr. Ahsan Choudhuri is Associate Vice President for Aerospace Center and Professor of Mechanical Engineering at the University of Texas at El Paso (UTEP). He is the founding Director of UTEP NASA MIRO Center for Space Exploration and Technology Research (cSETR) and holds the endowed Mr. and Mrs. MacIntosh Murchison Chair II in Engineering. Dr. Ahsan Choudhuri's academic career has evolved within the paradigm of UTEP's access and excellence mission. He is a part of UTEP's strategic vision to create abundant educational opportunities to ensure social mobility for the residents of the Paso Del Norte region.

Dr. Ahsan Choudhuri is an internationally renowned expert in aerospace and defense systems. He is the founding director of UTEP NASA supported Center for Space Exploration and Technology Research (cSETR). Dr. Choudhuri led the growth of UTEP's aerospace and defense and energy education and research program from infancy to a nationally recognized program. He has formed strategic collaborations and partnerships with NASA, DOE, DOD, and aerospace and defense industries. Dr. Choudhuri is a key institutional leader for developing and managing the partnership with Lockheed Martin and NASA. Dr. Choudhuri is a member of the Executive Committee of the Lunar Surface Innovation Consortium (LSIC), which supports NASA's Space Technology Mission Directorate.

Dr. Choudhuri is a proud alumnus of Khulna University of Engineering and Technology, where he received his B.S. in Mechanical Engineering. He received his M.S. and Ph.D. from the University of Oklahoma School of Aerospace and Mechanical Engineering.

Speakers

Timothy Cichan

Space Exploration Architect, Lockheed Martin

Timothy Cichan (Chee-haan) is the Space Exploration Architect at Lockheed Martin, where he leads a multi-disciplinary team of engineers who figure out how to help astronauts and robots visit the Moon, asteroids, and Mars. He previously was the Orion System Architect. Timothy joined Lockheed Martin in 2002, and has worked for both human spaceflight and commercial communication satellite teams, in optimal trajectory design, mission analysis, subsystem development, and systems engineering. He has a Master's and Bachelor's degree in Aerospace Engineering from Penn State.

Matthew Daniels

Assistant Director of the White House Office of Science and Technology Policy (OSTP) for Space Security & Special Projects

Dr. Matthew Daniels is currently the Assistant Director of the White House Office of Science and Technology Policy (OSTP) for Space Security & Special Projects. His work focuses on US space programs and technology strategy. Earlier he has served in multiple roles spanning space programs and artificial intelligence at NASA and the Department of Defense. Outside of the U.S. Government, he has been a Senior Fellow and research faculty at Georgetown's Center for Security and Emerging Technology, research affiliate at MIT and Stanford, and space technology advisor to MIT's Lincoln Lab. Matt started as a research engineer at NASA, with work in spacecraft design, stochastic control, and new science missions. He received his Ph.D. and M.S. degrees in engineering from Stanford, a B.A. in physics from Cornell, and was a Science Fellow at Stanford's Center for International Security and Cooperation. He is a recipient of the Department of Defense Medal for Distinguished Public Service.

Speakers

Walt Engelund

Deputy Associate Administrator for Programs, NASA Space Technology Mission Directorate

Mr. 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 $1Billion. 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, Mr. Engelund spent 30 years at NASA's Langley Research Center in Hampton, VA, most recently as the Director of the Space Technology and Exploration Directorate, where he led an organization that was responsible for developing technologies for human spaceflight and robotic exploration. 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, 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.

Israel (Fig) Figueroa

Director of System Architect & Solutions, Firefly Aerospace

Israel joined Firefly in August 2022 bringing over 22 years of experience in the Department of Defense (DoD) and National Reconnaissance Office (NRO) leading high performing teams as a space systems defense acquisition manager. Background includes diverse leadership roles in multiples organizations including as Service Operations Division Chief responsible for the integration and operations of NRO communications systems valued at $3.1B, as Senior Launch Acquisition Advisor to the Office of Space Launch developing multi-million-dollar acquisition strategies to launch Intelligence Community (IC) satellites and Chief Engineer of the Delta II Launch vehicle at the Launch and Range Systems Wing, Space and Missiles Systems Center in Los Angeles, CA. Israel holds an ME in Engineering Management from the University of Colorado, Colorado Springs and a BS in Electrical Engineering from the University of Puerto Rico, Mayaguez.

Speakers

Dr. Wesley Fuhrman

LSII Lead

Senior Professional Staff, JHU Applied Physics Laboratory

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

Kristina Gibbs

Deputy Director, Solar System Exploration Research Virtual Institute, NASA

Kristina Gibbs joined the Solar System Exploration Research Virtual Institute (SSERVI) as Associate Director, and subsequently assumed the position of Deputy Director in February 2020. SSERVI, located at NASA Ames Research Center, links competitively selected science teams across the nation working together to help lead the agency's research activities related to NASA's lunar exploration goals SSERVI research includes studies of the Moon (including lunar samples), from the Moon (using the Moon as an observational platform) and on the Moon (studies related to a human return to the Moon). In her current capacity, Kristina manages all institute operations and the international partners program. She provides strategic direction and oversees science management for the research teams, international partners, and the SSERVI Central team.

Kristina embarked on her career by supporting space life science payloads and collaborating with Russian scientists for biology experiments on the Mir Space Station. She went on to manage spaceflight payloads on the Space Shuttle and the International Space Station. Subsequently, she transitioned to contract management, supervising a department that supported virtual institutes, web and collaborative technologies teams, and education initiatives. Kristina's experience is diverse, encompassing project management of spaceflight research payloads, education and public outreach projects, international collaborations, hardware development, and forging innovative partnerships with NASA. Kristina brings extensive experience leading multidisciplinary teams and fostering communication across scientific, technical, and administrative organizations. Furthermore, she successfully managed several summer student research programs, including the NASA Ames Academy programs.

Kristina has been honored with the Space Flight Awareness Award, the "Silver Snoopy," and several NASA Ames and contractor management achievement awards. She holds a Bachelor of Science degree in Molecular and Cellular Biology from the University of Arizona, and she continues to pursue professional development in project management and leadership.

Speakers

Carla Haroz

AIL Operations Program Manager, National Science Foundation

Ms. Carla Haroz began her career with the National Science Foundation as the United States Antarctic Program (USAP) Operations Program Manager in November 2021. Her responsibilities include day-to-day management of operations at all three USAP stations, including responsibility for emergency response, fleet, fire response, waste management, fuels, heavy traversing, and airfields.

Prior to NSF, Ms. Haroz worked at NASA Johnson Space Center for the International Space Station Flight Operations Directorate (FOD) for 23 years. She held several flight controller positions in support of the ISS systems, such as environmental control, life support, thermal, electrical power, international partner integration, and was the voice to the crew as a CAPCOM. Carla spent the majority of her NASA career as a technical liaison between Mission Control Moscow and Mission Control Houston, leading a team of American flight controllers working real time operational support in Moscow, Russia. She trained American astronauts in Star City, Russia on Russian systems found onboard the ISS. She has amassed several thousand hours working flight control, many for dynamic operations; such as crewed and cargo vehicle dockings, ISS reboosts, and has had to handle emergency situations onboard from fires to possible depressurizations.

Ms. Haroz was also the manager for multiple flight control groups in FOD: the International Liaison Office, the Integrated Systems Engineers Group, and the Vehicle Operations and Systems Integrations Group (callsign MAVRIC), a team of 40 flight controllers that integrate ISS operations internationally and with commercial crew partners.

Ms. Haroz has obtained the following degrees: M.S. Aeronautics and Astronautics from the Massachusetts Institute of Technology, M.S. Arctic Engineering from the University of Alaska, B.S. Aerospace Engineering from the University of Texas at Austin, and a B.A. Russian Language and Literature also from the University of Texas at Austin.

Dr. Rachel Klima

Director, LSIC
Principal Staff Scientist, JHU Applied Physics Laboratory

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

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

Speakers

Philip M. Lubin

Professor, University of California, Santa Barbara

Philip Lubin is a professor of Physics at UC Santa Barbara whose primary research has been focused on studies of the early universe in the millimeter wavelengths bands as well as applications of directed energy for planetary defense and relativistic propulsion. His group has designed, developed and fielded more than two dozen ground based and balloon borne missions and helped develop two major cosmology satellites. Among other accomplishments his group first detected the horizon scale fluctuations in the Cosmic Microwave Background from both their South Pole and balloon borne systems twenty years ago and their latest results, along with an international teams of ESA and NASA researchers, are from the Planck cosmology mission which have mapped in exquisite detail the structures of the early universe. He is a co-I on the Planck mission. His group has worked on applications of directed energy systems for both small scale single launcher solutions as well as large standoff systems for planetary defense and on applications to allow small interstellar probes to achieve relativistic speeds for the first interstellar missions. He is co-recipient of the 2006 Gruber Prize in Cosmology along with the COBE science team for their groundbreaking work in cosmology as well as the 2018 Gruber Prize in Cosmology along with the Planck science team for their determination of fundamental cosmological parameter. He has published more than 450 papers.

Dr. James Mastandrea

Acting Surface Power Lead and MOSA Working Group Lead, LSIC
Senior Professional Staff, JHU Applied Physics Laboratory

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

Speakers

Pam Melroy

Deputy Administrator, NASA

Col. (USAF, ret) Pam Melroy was sworn in as the NASA deputy administrator on June 21, 2021.

As deputy administrator, Melroy performs the duties and exercises the powers delegated by the administrator, assists the administrator in making final agency decisions, and acts for the administrator in his absence by performing all necessary functions to govern NASA operations. Melroy is also responsible for laying out the agency's vision and representing NASA to the Executive Office of the President, Congress, heads of federal and other appropriate government agencies, international organizations, and external organizations and communities.

Melroy was commissioned through the Air Force Reserve Officers' Training Corps (ROTC) program in 1983. As a co-pilot, aircraft commander, instructor pilot, and test pilot, Melroy logged more than 6,000 flight hours in more than 50 different aircraft before retiring from the Air Force in 2007. She is a veteran of Operation Desert Shield/Desert Storm and Operation Just Cause, with more than 200 combat and combat support hours.

Melroy was selected as an astronaut candidate by NASA in December 1994. Initially assigned to astronaut support duties for launch and landing, she also worked on advanced projects for the Astronaut Office. She also performed Capsule Communicator (CAPCOM) duties in mission control. In addition, she served on the Columbia Reconstruction Team as the lead for the crew module and served as Deputy Project Manager for the Columbia Crew Survival Investigation Team. In her final position, she served as Branch Chief for the Orion branch of the Astronaut Office.

One of only two women to command a space shuttle, Melroy logged more than 38 days (924 hours) in space. She served as pilot on two flights, STS-92 in 2000 and STS-112 in 2002, and was the mission commander on STS-120 in 2007. All three of her missions were assembly missions to build the International Space Station.

After serving more than two decades in the Air Force and as a NASA astronaut, Melroy took on a number of leadership roles, including at Lockheed Martin; the Federal Aviation Administration; the Defense Advanced Research Projects Agency; Australia's Nova Systems Pty Ltd; and as an advisor to the Australian Space Agency. She also served as an independent consultant and a member of the National Space Council's Users Advisory Group.

Melroy holds a bachelor's degree in physics and astronomy from Wellesley College and a master's degree in Earth and planetary sciences from the Massachusetts Institute of Technology.

Michael Provenzano

Director of Lunar Surface Systems, Astrobotic

Mike is responsible for leading the development of Astrobotic's planetary rover and power infrastructure technologies. He leads a mixed team of professionals to develop the world's first commercial lunar rovers and pioneered the mobility as a service model for lunar payloads. Mike's team is also responsible for leading the development of the Moon's first lunar power grid: LunaGrid, powered by Astrobotic's Vertical Solar Array Towers and the first space qualified wireless charging systems.

An entrepreneur, formerly selected as Poets and Quants Top 100 Global MBAs, Mike specializes in making early technologies marketable. Mr. Provenzano started Astrobotic's Lunar Surface Systems department and has a history managing complex space projects, including work on the Boeing Space Launch System (SLS), and leading the development of an NSF-funded I-Corps Site Team at Carnegie Mellon researching electromagnetic transportation from the lunar surface.

Speakers

James Reuter

Associate Administrator, NASA STMD

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

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

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

Michael Sims

Founder and CEO, Ceres Robotics

Sims is Founder and CEO of Ceres Robotics Inc. Prior to Ceres Robotics, Sims was a Senior Scientist at Mars Institute, Vice President at Moon Express and a 20+ year veteran of NASA. During that time, he worked on artificial intelligence and robotics principally focused on planetary rovers, including Mars Pathfinder, and Mars Spirit and Opportunity missions.   His Ph.D. is from Rutgers University looking at the application of machine learning for discovery in mathematics.

Stefanie Tompkins

Director, Defense Advanced Research Projects Agency

Dr. Stefanie Tompkins is the director of the Defense Advanced Research Projects Agency (DARPA). Prior to this assignment, she was the vice president for research and technology transfer at Colorado School of Mines.

Tompkins has spent much of her professional life leading scientists and engineers in developing new technology capabilities. She began her industry career as a senior scientist and later assistant vice-president and line manager at Science Applications International Corporation, where she spent 10 years conducting and managing research projects in planetary mapping, geology, and imaging spectroscopy. As a program manager in DARPA's Strategic Technology Office, she created and managed programs in ubiquitous GPS-free navigation as well as in optical component manufacturing. Tompkins has also served as the deputy director of DARPA's Strategic Technology Office, director of DARPA's Defense Sciences Office – the agency's most exploratory office in identifying and accelerating breakthrough technologies for national security – as well as the acting DARPA deputy director.

Tompkins received a Bachelor of Arts degree in geology and geophysics from Princeton University and Master of Science and Doctor of Philosophy degrees in geology from Brown University. She has also served as a military intelligence officer in the U.S. Army.

Speakers

Dr. Paul van Susante

Assistant Professor Mechanical Engineering - Engineering Mechanics, Michigan Technological University

Dr. van Susante is an assistant professor at Michigan Technological University in the Mechanical Engineering – Engineering Mechanics Department and the founder and PI of the Planetary Surface Technology Development Lab (PSTDL), also known as HuskyWorks. Dr. van Susante's research focuses on robotic systems for In-Situ Resource Utilization (ISRU) and construction and in particular robotic mechanical systems under lunar and mars conditions interacting with the lunar and Mars surface. He is actively researching, developing and testing technologies under lunar and mars environmental conditions for detecting volatiles in lunar regolith, determining geotechnical properties of lunar regolith, conveying and compacting lunar regolith, excavating (cemented) lunar regolith, excavating gypsum and extracting water from excavated gypsum and buried glaciers for Mars applications as well as developing power transfer via (superconducting) tether into the lunar Permanently Shade Regions. Dr. van Susante is PI on multiple NASA and industry funded ISRU projects with a combined value of over $4M. More information can be found at: https://www.huskyworks.space

Harri Vanhala

Lunar Surface Technology Research Lead, Space Technology Research Grants Program, 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.

Speakers

Kurt (Spuds) Vogel

Director of Space Architectures, NASA

Dr. Kurt "Spuds" Vogel is the director of space architectures within the office of the Administrator at NASA Headquarters in Washington, D.C. He was appointed to the position and sworn in by Deputy NASA Administrator Pam Melroy on July 19, 2021.

Dr. Vogel comes to NASA with over 32 years of U.S. government service, primarily in the Defense Department, as a technical leader, senior program manager, and chief technologist.

Prior to his NASA appointment, Dr. Vogel served 6 years at the Defense Advanced Research Projects Agency (DARPA) leading innovative research in stealth technology, electronic warfare, air-space integration, and space control systems. He managed a portfolio of classified, state-of-the-art, high-risk programs that spanned multiple DARPA offices, including both the Tactical Technology Office (TTO) and the Strategic Technology Office (STO).

Before joining DARPA, Dr. Vogel led research & development efforts at the Air Force Research Lab's Systems Technology Office (AFRL STO) where he directed the Defense Department's only science & technology portfolio, and the corresponding national tech base, for a highly-classified mission area. He oversaw 35 emerging technology areas with the goal of protecting the DOD's most valuable weapon systems. He also served as the acting Chief Technologist for the National Reconnaissance Office's Survivability Assurance Office (NRO SAO).

Dr. Vogel retired from active duty in 2010 after serving over 21 years as an Air Force officer in both the air and space domains. He was the 8th officer to lead the USAF Red Team in it's 40+ year history, and was the first Red Team Chief to incorporate the space domain into the nationally-recognized team's charter. He is a graduate of the USAF Test Pilot School, and has flown over 40 types of aircraft as a flight test engineer and civilian pilot. He was also the Chief Technology Officer for the Next Generation Bomber program, and led the production acceptance program for all B-2's in the U.S. inventory.Dr. Vogel has served in a variety of other assignments that span work in U.S. foreign policy initiatives, prototype flight test, space test and operations, spacecraft design, advanced orbital dynamics, satellite operations, and other Presidentially-directed research and development programs in the air and space domains.

Table of Contents for Abstracts

Table of Contents for Abstracts

Page # **Presenter, Title**

Table of Contents for Abstracts

Spatiam DTN Platform: a commercially managed platform supporting open network overlays to communicate using Delay and Disruption Tolerant Networking.

V. Acosta[1] and Dr. A. Montilla[1], [1]Spatiam Corporation, 1200 Conroe Dr, Allen, TX 75013 (Contact: vero@spatiam.com)

Introduction: From activities in Low Earth Orbit, (LEO) to science experiments in the International Space Station (ISS) to landing rovers on Mars, the commercial space industry is beginning to accelerate its growth. With this, enabling connectivity and collaboration between agencies and commercial organizations will require an interoperable, secure, and reliable network of networks in space.

Network operations in the International Space Station (ISS) have shown the challenges ahead for future commercial space missions, as users and applications such as landers, relay orbiters, human space exploration, science and commercial experiments, and spacecraft increase in number. Whether it is in Earth's orbit, the Moon, or deep space, communication and access will become challenging, primarily due to high volumes of data generated by experiments and operations, significant distance delays in deep space missions, and link disruption associated with operating in space. In overcoming these challenges, NASA (and the European Space Agency, ESA) is requiring the use of Delay and Disruption Tolerant Networking (DTN) for LunaNet, the Lunar Internet architecture [1] [2] that will provide terrestrial 'internet-like' interoperable, secure, and reliable interplanetary communications network and data delivery.

Spatiam DTN Platform: The Spatiam DTN Platform aims to power space communications with operational DTN. The Spatiam DTN platform is designed to enable space and ground assets to connect and transfer data efficiently on the Lunar surface, around the Moon, and to/from the Moon and Earth, supporting multi-administration and interoperable network overlays. to communicate using Delay and Disruption Tolerant Networking, through three main platform capabilities: the DTN Manager, DTN Managed Instances and the DTN CLI.

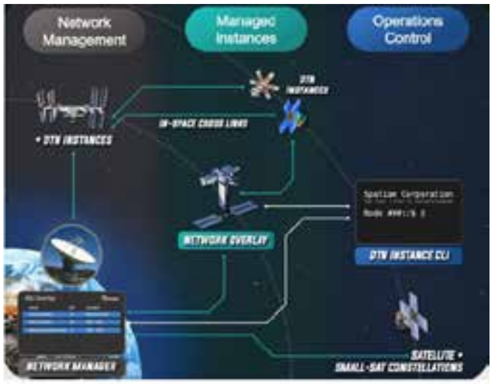


Figure 1 Spatiam DTN Platform

Demonstrations: In partnership with the European Space Agency (ESA) and D3TN GmbH, Spatiam corporation tested the interoperability between different implementations of DTN communication protocols and validated an image recognition application leveraging Google's Cloud Vision API.

Interoperability was tested between µD3TN (by D3TN) and ION (by NASA/JPL) Bundle Protocol implementations, leveraging ESA's OPS-SAT Small Satellite to include the constraints of limited computing power, short satellite passes, and bandwidth limitations that currently exist in space. The experiment resulted in the successful interoperability of multiple DTN nodes running different Bundle Protocol (BPv7) implementations.

With the help of the Interplanetary Networking Interest Group (IPNSIG), we ran an additional experiment to validate both, interoperability of multiple implementations while supporting a specific application. . The application received images over the DTN network, gathered image labels from Google's Cloud Vision API, and forwarded them to the original sender. We successfully validated providing Cloud (AI) services via DTN and tested how the network handles larger data payloads.

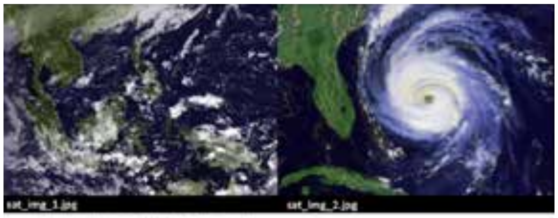


Figure 2 Cloud vision application test images

References:

[1] David J. Israel et al. (1997) LunaNet: Flexible and Extensible Lunar Exploration Communications and Navigation Infrastructure
[2] Burleigh, Scott, Adrian Hooke, Leigh Torgerson, Kevin Fall, Vint Cerf, Bob Durst, Keith Scott, and Howard Weiss. "Delay-Tolerant Networking: An Approach to Interplanetary Internet." IEEE Communications Magazine 41, no. 6 (2003): 128-136.

Design, Protection & Control of Lunar Surface Dc Microgrids utilizing WBG based Flexible Dc Energy Router N. Adina[1] and J. Wang[1]. [1]The Ohio State University (Contact: adina.1@osu.edu)

Introduction: Reliable operation of lunar based power systems is essential to carry out critical research activities and support life on the surface of the moon. A three layered design, protection and control of the lunar dc microgrids is proposed utilizing WBG based Flexible Dc Energy Router (FeDER) [1-2], shown in Fig. 1, which is as follows; (a) Graph Theory & Fault Diagnostics for Sustainability & Resilience (b) Energy Management System and (c) Smart Resistor Control.

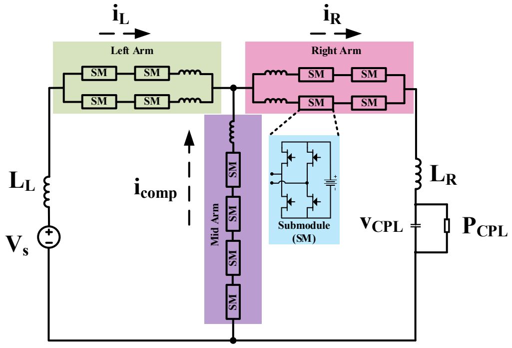


Fig. 1: Illustration of the concept of the Flexible Dc Energy Router (FeDER) in a single-source single-load system.

Three Layered Design, Protection and Control: The three layered approach is considered to design and operate the conceptual interconnected lunar dc microgrid shown in Fig. 2, which is realized with a ring architecture. The graph theory [3] based planning is utilized to enhance the overall system resiliency. Fault diagnostics [4] to ensure fault detection and isolation, actuating the FeDER's in the lunar microgrid. The effective coordination and dispatching of distributed energy resources in the dc microgrid is realized with the energy management system to meet the load demand on the surface of the moon. Finally the smart resistor control [1-2] of the FeDER in the lunar microgrid enables in power quality improvement (transient stability) and power flow control (power transmission) within interconnected dc microgrids.

Hardware Testbed with Power Hardware in the Loop: A 120 V, 10kW hardware testbed and the real time platform is currently under development to emulate the lunar dc microgrid shown in Fig. 3. Different testcases will be demonstrated showcasing the three layered approaches.

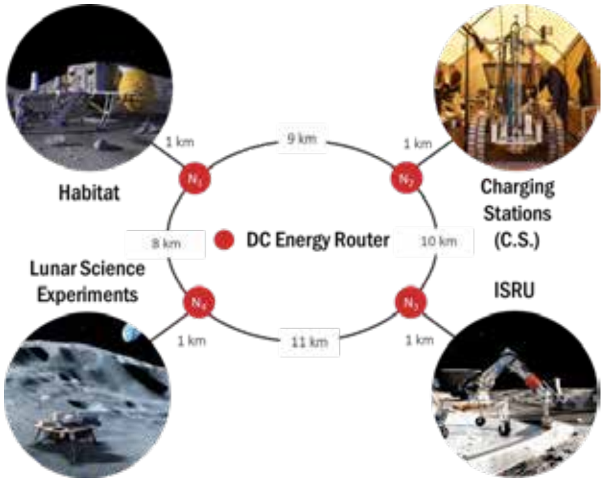


Fig. 2: Conceptual Lunar Dc Microgrid interfaced with Flexible Dc Energy Router (FeDER).

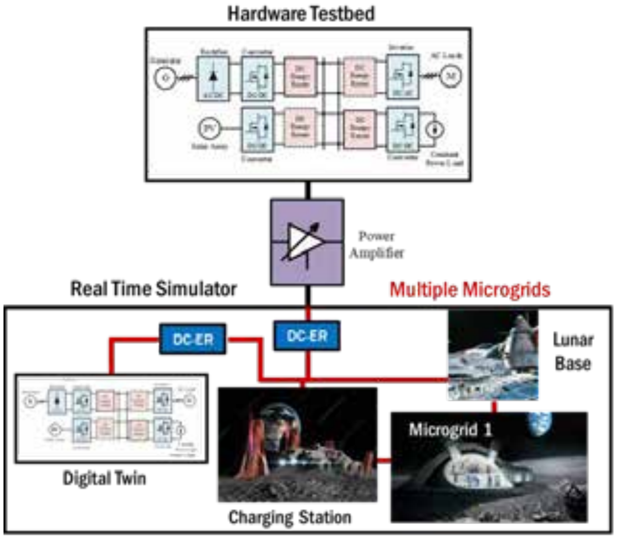


Fig. 3: Lunar Dc Microgrid Testbed.

References:

[1] K. A. Potty et al. (2020), "Smart Resistor: Stabilization of DC Microgrids Containing Constant Power Loads Using High-Bandwidth Power Converters and Energy Storage," in *IEEE Transactions on Power Electronics*. [2] Y. Zhang et al. (2021) "T-Type Modular Dc Circuit Breaker (T-Breaker) for Future Dc Networks," *(APEC)* [3] B. Guddanti et al. (2022), "Resiliency-Based Planning for Interconnected Lunar Microgrids using Hybrid-Edge Rewiring," IEEE (I&CPS) [4] G. Heyer et al. (2023) "Optimal Sensor Placement for Fault Detection and Isolation in a Lunar DC Microgrid" AIAA SciTech

Lunar Exploration and Science Orbiter (LExSO) MISSION: FUTURE LUNAR SCIENCE AND SURFACE EXPLORATION. M. Amato (Michael.Amato@nasa.gov), N. Petro, C. Baker, B. Cohen, E. Mazarico, E. Park, J. Staren, C. Achellies,[1], S. Lawrence[2], [1]NASA Goddard Space Flight Center, [2]NASA Johnson Space Flight Center

Introduction: A small team is developing the Lunar Exploration and Science Orbiter (LExSO) mission concept to meet critical future lunar exploration and science measurement needs. LExSO is a lunar orbiter capable of accommodating a payload suite of highly capable instruments. The mission will contribute to answering science questions about: surface geology; volatiles; and in addition to science, support exploration needs. A preliminary science team is working to define the science needs for a next generation orbital mission based on previous community input reports. Important science questions have been defined by the broader science community in the recent Lunar Exploration Analysis Group Continuous Lunar Orbital Capabilities Specific Action Team (LEAG CLOC SAT) Report, the Artemis III Science Definition Team and the 2023 - 2032 Planetary Science and Astrobiology Decadal Survey Report. The LExSO mission will significantly contribute to our understanding of the Moon with new science and improved measurements over the existing wealth of data on hand.

The mission concept is in pre-Phase A study with a science and engineering team based out of NASA GSFC who developed and currently operate LRO. The core team developing LExSO has experience with lunar missions in low lunar orbit such as LRO and LADEE.

The Need for LExSO: LEAG's CLOC-SAT report clearly articulates the scientific need for continued orbital presence at the Moon. LRO is beyond its design lifetime and may not operate past the first few Human Artemis landing missions (fuel is expected to run out as soon as 2027,). Foreseeing a gap and new needs in orbital science, LExSO has started the first study step in formulation and to enable timely progress into development. LRO has been one of the most critical contributors to lunar science measuring anthropogenic as well as natural changes to the surface that can critically impact human exploration planning and safety needs. LExSO will address science and exploration drivers with increased measurement capabilities and has more orbital adjustment flexibility. LExSO will fill Artemis situational awareness, planning, and science gaps and with enhanced capability, enables improvements to the LRO imagery and localized topography.

LExSO Concept Development: LExSO is in pre-Phase A in FY 23 and will advance to Phase A in FY24. NASA Science Mission Directorate, Artemis and Exploration Systems Development Mission Directorate and the lunar science community are the key stakeholders in LExSO. As the concept matures, we expect opportunities to evolve the science team.

LExSO goals: LExSO science goals are largely driven by the anticipated CLOC SAT report as well as exploration/Artemis needs that the team has distilled into an initial set of mission objectives. A LExSO 'pre science team' has been organized in three major working groups: Surface Geology, Resources/Volatiles. and Exploration. These science working groups are working together with stakeholders, engineering, management to prioritize the goals and measurements. The goals, and exploration/Artemis inputs are being worked to derive a cohesive mission that advances lunar science on its own by addressing a swath of the highest priority measurements, and provides important exploration support.

LExSO Mission: LExSO is envisioned to be a NASA Discovery class-like mission, reflecting the need for higher capability instruments and orbit adjustment flexibility. LExSO goals and measurements are being carefully worked to provide a comprehensive suite including global measurement capabilities as well as high resolution volatile/resource assessments, imagery, and topography of select regions. The LExSO mission team is leveraging knowledge and lessons learned gained from LRO to formulate a mission that will serve lunar science and exploration to fundamentally change our understanding of the Moon and its processes.

The team is excited to work with the community on what will be a critical and important science and exploration mission.

Acknowledgments: The LExSO team, NASA SMD ESSIO and ESDMD.

Additional Information: For additional information please contact Michael Amato, Noah Petro or Betsy Park at NASA GSFC.

Light Water Analysis and Volatile Extraction (Light WAVE). Aaron. J. Paz and Koorosh Araghi, NASA Johnson Space Center (2101 NASA Parkway, Houston TX 77058; Aaron.Paz-1@nasa.gov)

Introduction: The presence of water ice in permanently shadowed regions on the lunar surface may enable a sustained human presence on the Moon with minimal need for consumables. The first step toward utilizing lunar water ice to advance human space exploration will be to determine the abundance, accessibility, and distribution of this valuable resource

Current Knowledge of Lunar Water Ice Concentration: We currently have one data point for lunar water concencentration, which was determined to be 5.6% +/- 2.9% water by mass in Cabeus crater by the LCROSS mission [1]. The upcoming PRIME-1 and VIPER missions should provide more data, but these are the first steps toward a campaign that will likely be necessary in order to determine appropriate locations and requirements for lunar water ice mining [2]. Future missions will be necessary to acquire more knowledge and also to demonstrate critical functions such as icy regolith handling and water capture that will be necessary for In-Situ Resource Utilization.

State of the Art: The upcoming water prospecting missions PRIME-1 and VIPER both use a drill and mass spectrometer to detect water. However, water is intentionally released to the vacuum of space so the functions of volatile retention and water capture will not be addressed. The ProSPA instrument being developed by the European Space Agency requires icy regolith sample handling, but the small sample size and finite number of sample containers could restrict ProSPA from being utilized during mobile prospecting missions.

Light WAVE: The Light Water Analysis and Volatile Extraction system was designed to capture icy regolith samples acquired from a drill. Regolith samples are then weighed, sealed, and heated to release volatiles. Volatiles are captured in a volume with a known temperature and the ideal gas law is used to determine the total quantity of volatiles in the volume. The composition of the volatile mixture is determined using a mass spectrometer so that each volatile can be quantified. By quantifying the amount of water extracted from the regolith sample, and acquiring the mass of the sample, volatile concentration by mass can be determined. The relatively large sample containers used in LightWAVE, combined with no inherent limit on the number of samples that can be processed, make this system capable of capturing enough water to enable a lunar water sample return mission, and makes it ideal for mobile prospecting missions.

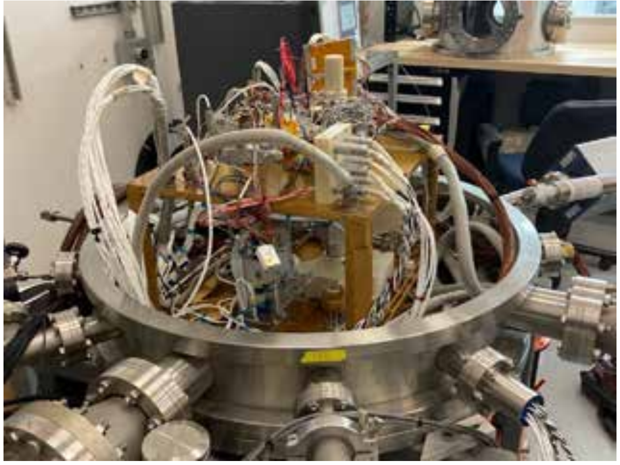


Figure 1: LightWAVE System

References:

[1] Colaprete, A., et. al.(2010). Detection of water in the LCROSS ejecta plume. *science*, *330*(6003), 463-468. [2] Kleinhenz, J.,et. al. (2020). *Lunar Water ISRU Measurement Study (LWIMS): Establishing a Measurement Plan for Identification and Characterization of a Water Reserve* (No. E-19884).

LUNAR DEVELOPMENT & TEST FACILITY, JSC B351

Michael Reddington and Koorosh Araghi, NASA Johnson Space Center, 2101 NASA Parkway, Houston, Texas 77058. (Contact: michael.reddington-1@nasa.gov)

Introduction:
In anticipation of extended operations on the lunar surface, JSC Building B351 has been prepared to meet test needs to mature technologies that extract resources from lunar regolith, handle lunar regolith or must perform in a dusty lunar environment. Domains such as In-Situ Resource Utilization (ISRU), dust mitigation, power generation and distribution, robotics and surface tools will all require testing with lunar regolith/simulants to demonstrate flight readiness. The Lunar Development and Test Facility (LDTF) houses environmental test capabilities, including lunar simulants, geared toward advancing Technical Readiness Level (TRL) of these lunar surface technologies. Seen as an agency need to enable and demonstrate new technologies, a portion of the facility capability was developed under the "Dirty Lunar Surface Simulation" project in FY2020, funded by the NASA Game Changing Development program. Some current uses include testing of an oxygen extraction from lunar regolith test, a spacesuit cleaning tool evaluation and a study to measure dust effects on space radiators (thermal management).

Facility capabilities include a Simulant Preparation Area, Settling dust chamber, Component TVAC chamber, Dusty Glove Box and a 15ft thermal vacuum chamber. A majority of the lunar simulant handling is done in the Simulant Preparation Area (Fig 1). This area is equipped with particle monitoring, HEPA filtering and operational protocols to safely perform simulant handling. In this area, simulants and be dried or mixed to desired water /simulant ratio (for icy-regolith).

Fig 1- Simulant Preparation area (left), Settling Dust Chamber (right)

Also located in the area is a Settling dust chamber (Fig1). This is an ambient pressure capability that dusts and re-dusts components with lunar simulant at designated intervals. This is especially helpful for moving test articles that need dust reapplied to maintain a specific level of dust accumulation on it.

Large beds or drill tubes are also prepared in the Simulant prep area (Fig 2). Any mixing and compaction is done in this room prior to loading in the 15ft thermal vacuum chamber.

Fig 2- Chamber Drill Tube and Regolith Bin in Simulant Prep Area (left), Component TVAC (right)

Component level environment testing with dust can be performed in the 3ft vacuum chamber (cube). The chamber is capable of vacuum levels down to 10^{-6} torr and has zoned controlled shroud walls capable of temperatures ranging from -300°F to +300°F.

15ft thermal chamber is used for sub-system and system level testing (Fig 3). Originally built to test fuel cells and later used for high energy batteries. The chamber was upgraded with dust mitigation for its vacuum system to allow for testing with dust and/or regolith beds. The chamber is capable of 10^{-6} torr and shroud range of -300°F to +250°F.

Fig 3- 15ft Thermal Vacuum Chamber with Spacesuit dust mitigation test equipment installed

LUNAR WATER EXTRACTION via LUNAR AUGER DRYER ISRU (LADI).

Jacob Collins[1] and Koorosh Araghi[2], [1&2]NASA Johnson Space Center, 2101 NASA Parkway, Houston, Texas 77058. (Contact: jacob.collins-1@nasa.gov)

Introduction: In 2009, the Lunar Reconnaissance Orbiter (LRO) and Lunar Crater Observation and Sensing Satellite (LCROSS) provided definitive proof of water in the Lunar's southern permanently shadowed region (PSR)[1]. Both the 2020 NASA Technology Taxonomy[2] and the Lunar Surface Innovation Initiative (LSII) team identified capability gaps in icy regolith transfer and reactor processing in Permanently Shadowed Region (PSR) environmental conditions. A water processing plant operating from inside the PSR can continuously process water (and volatiles) for both breathable air and propellant. NASA's Johnson Space Center (JSC) began development of the primary sub-system for a Mars plant in 2017 and fabricated a unique breadboard test stand for validating the feasibility of this concept. This testing was postponed with the redirection of NASA's mission from Mars to Moon. A JSC led trade study[3] in FY20 formulated a plan to leverage existing hardware to test concept feasibility, developed a lunar auger dryer sizing tool, and identified that both physical flow and thermal models are required to develop an Engineering Development Unit (EDU) for environmental testing.

The major subsystems of a lunar water processing plant include a.) an upstream excavation rover and a hopper/size-sorter, b.) an auger dryer, and c.) a downstream cold trap used for ice deposition (water vapor to ice). The top-level concept of operations begins with the excavator digging up icy regolith and delivering it to a stationary ISRU processing plant (inside PSR), size sorting the feed to remove large rocks, and then discharging into a hopper. The hopper feeds the regolith to an auger-dryer which extracts water from the soil and then sends it to a cold trap subsystem. The dried regolith is collected, dumped (potentially processed for waste heat), and the excavator repeats the process. Ice deposition occurs in the cold trap as vapor is converted into ice, impurities removed, and the product stored on a tanker. This tanker will either travel out of the PSR to a stationary electrolyzing processing plant located on the crater ridge or the tank will be pressurized, and liquid water pumped to the plant via flex hose. At the crater ridge, the water is cleaned, electrolyzed into oxygen and hydrogen, liquefied, and finally stored.

The key design features of the auger dryer design is operating below the triple point of water and using a variable pitch auger to create a 100% full regolith plug-seal at the inlet and outlet of the auger with a 15% full heated section. These features maintain low internal pressure (easier to sustain regolith plug), prevent liquid water (increases motor torque and initiates equilibrium chemistry with impurities), and eliminate the need for isolation valves. Isolation valves increase system height, mass, complexity, and reduces reliability.

The breadboard auger dryer, shown in Figure 1, has the unique capability to operate with either a clear or stainless-steel casing supporting both mechanical and thermal test requirements. The test stand was setup in JSC's dust containment test cell.

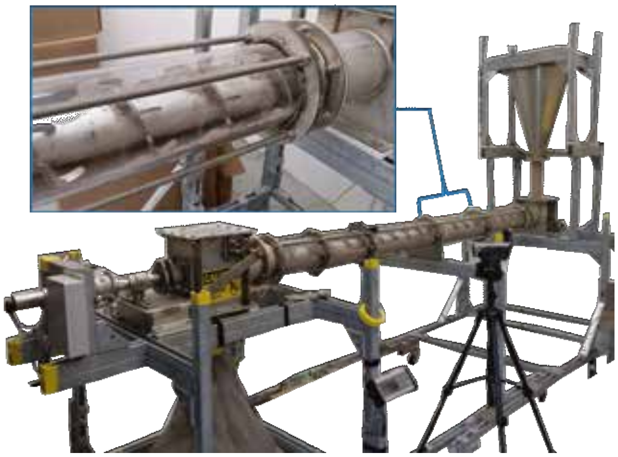


Figure 1 – LADI Breadboard (clear casing installed)

Nineteen mechanical and multiple thermal test runs were completed using Exolith Lab's Lunar Highlands Simulant (LHS-1) increasing the breadboard system to TRL 4. Five unique auger geometries, shown in Figure 2, and three motors configurations were used to optimize steady state flow. Torque, RPM, mass flow rate, gate angle, and power were measured while observing discharge plug behavior.

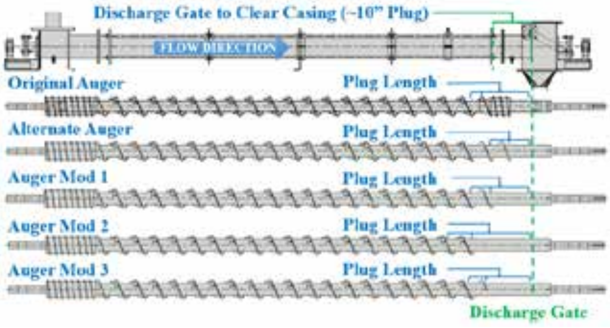


Figure 2 – Auger Configurations Tested

[1] A. Colaprete et al. (2010) *Detection of Water in the LCROSS Ejecta Plume, Science, Vol 330*. [2] D. Terrier (2020) *NASA Technology Taxonomy*, *NASA*. [3] J. Collins and L. R. Erickson (2021) *Lunar Auger Dryer ISRU (LADI) FY20 Formulation Report, JSC-67579 Internal Note.*

Multi-astronaut training with XR Redirected Walking

Qi Sun[1] , M. Arias-Estrada[2], A.Nemirovsky[2]
[1]NYU Tandon School of Engineering, New York, NY, [2]Orbital Outpost X, Inc, Santa Clara, CA.
(Contact: ariasm@orbitaloutpostx.com)

Introduction: Building infrastructure in the moon will require specialized training and collaboration for astronauts. In order to scale training for more astronauts an alternative is the use of eXtended Reality (XR) scenarios with "augmented" objects which are real objects that are seen as complex prototypes in the virtual scenario, that the users can manipulate or assemble collaboratively. The cost and flexibility of working with 3D models and simplified prototypes, make it cost effective for first training stages for future astronauts, or for creating particular training scenarios where a physical prototype would be too costly or not yet fully built.

We present a Virtual Reality (VR) simulation platform for astronaut training. The platform can host 2 astronauts for collaborative training and a third participant as an external mission controller that directs the training. The platform integrates the Redirected Walking (RW) technique, which tricks the users in the walkable space, to have the impression they are moving in a larger virtual area to the actual physical facility.

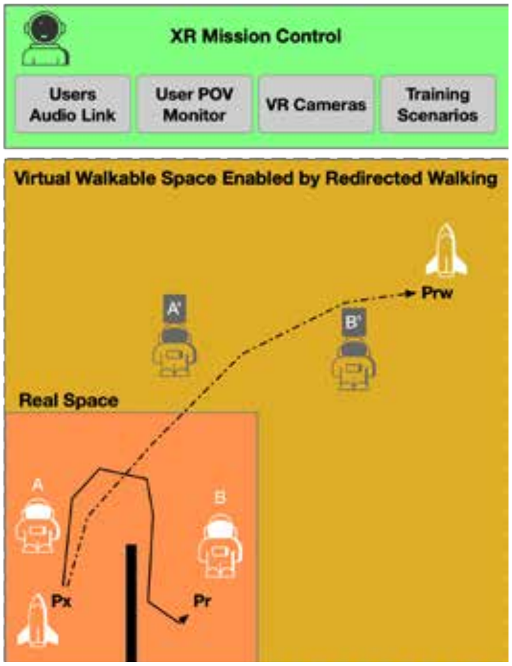


Figure 1. Redirected walking: users walk around the orange area but they have the impression of walking in the extended area in VR.

Figure 2. Two astronauts cooperating in VR space.

RW is carried out inside the VR headsets by introducing and accumulating unperceivable visual scenario shifts/rotations during normal eye saccadic motion which gives the user the impression of heading in a direction while physically they are moving around the physical space. Complex training scenarios can be simulated in conference room size areas, like 5x5 meters, by increasing to 4-5 times the perceived walkable area (ie. 10x10 meters).

The platform is a first step in the development of complex training tools where humans and semiautomated systems may collaborate for training, mission support, and mission planning.

In this presentation we will give an overview of the architecture, the RW principles and a video demo of the platform to show capabilities and potential opportunities for lunar infrastructure immersive simulation and collaboration.

References:

[1] hapira, O., Lu, J., Asente, P., Zhu, S., McGuire, M., Luebke, D., & Kaufman, A. (2018). Towards virtual reality infinite walking: Dynamic saccadic redirection. ACM T. on Graphics, 37(4).

[2] Dong, Z.-C., Wu, W., Xu, Z., **Sun, Q.**, Yuan, G., Liu, L.; Fu, X.-M. (2021). Tailored reality: Perception-aware scene restructuring for adaptive VR Navigation. ACM T. on Graphics, 40(5), 1–15.

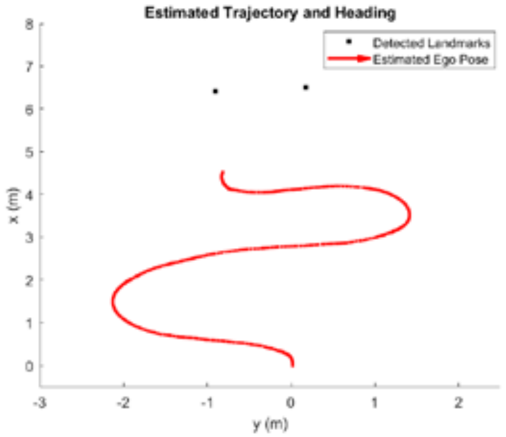
This project is supported by NASA STTR Phase I T11.06 grant (2022).

Visual SLAM for Lunar Navigation Using Skid Steer Dynamic Controls. Banerjee R., Higger M., Dreyer C., Petruska A. J. , Colorado School of Mines, 1500 Illinois St., Golden, CO, (Contact: rikbanerjee@mines.edu and mhigger@mines.edu)

Introduction: With the new wave of extra-terrestrial resource extraction and exploration , navigation on extra-terrestrial surfaces is increasingly important [1]. The NASA LuSTR mission seeks to develop technology for lunar robotic site preparation. This will require accurate real-time navigation and mapping. Since there is no a priori information about the environment where the rover will land, it will utilize a Simultaneous Localization And Mapping (SLAM) algorithm to store the positions of detected landmarks while estimating it's own trajectory. The lunar environment poses some challenges - GNSS-denied navigation, loosely-packed regolith, and sparse visual features. Thus when adapting terrestrial SLAM methods for extra-terrestrial navigation, these challenges have to be accounted for.

There are two major innovations proposed to address these problems for SLAM-based navigation. The first innovation is to estimate the slippage of the rover alongside the position, velocity, and orientation. This allows for compensation for the difficulties caused by the low-gravity regolith and improves the overall fidelity of the solution. A closed form description of the dynamics and associated sensitivities have been developed. This allows the system to estimate it's state as well as compute the related covariances at a low computational cost. This enables the rover to know when it is stuck. Secondly, a multilateration technique is proposed that estimates the position of nearby lunar rocks, which have distinct features from the surface of the moon. The sensor used provides a color image as well as a depth map. Thus, the system is able to extract 3D positions in a body fixed frame and through a measurement model, estimate the position of the rocks in the inertial frame. Each rock can be identified and a unique identifier is stored in the model. Thus, a map is built as the robot explores the landing site, even without having all the rocks in view at the same time.

An Extended Kalman Smoother-based SLAM algorithm has been developed that incorporates these complexities for trajectory estimation and mapping. This system is tested in a GNSS-denied environment and compared to off-the-shelf visual SLAM hardware.



[1] R. P. Mueller, R. E. Cox, T. Ebert, J. D. Smith, J. M. Schuler and A. J. Nick, "Regolith Advanced Surface Systems Operations Robot (RASSOR)," 2013 IEEE Aerospace Conference, Big Sky, MT, USA, 2013, pp. 1-12, doi: 10.1109/AERO.2013.6497341.

Investigations toward a Sustained, Efficient Presence on the Lunar Surface: Identifying and Scoping Technology Needs for Maximizing Use of In-Situ Materials. J. R. Berdis[1], J. Domenico[1], M. E. DeCoster[1], M. E. Nord[1], Ali Ramazani[1], I. Stanish[1], and M. Trexler[1]. [1]Johns Hopkins University Applied Physics Laboratory, Laurel, MD, USA. (Contact: email address Jodi.Berdis@jhuapl.edu)

Motivation: The posture of the United States Department of Defense (DoD) towards a Cislunar and lunar presence has kicked off a paradigm shift in space operations. Traditionally, the DoD has viewed its domain of influence in space to extend to 22,000 miles above the Earth (GEO), because national interests have been terrestrially focused. As modern space missions increasingly journey through the Cislunar domain and a lunar resource ecosystem emerges, there is an increasing need to expand the distance of national domain of influence by an order of magnitude to include the Moon. Progress towards realizing a paradigm shift in future DoD space operations includes the removal of the tyranny of Earth based launch (where structures are built on-orbit from extraterrestrial material) and establishing a persistent presence in the domain. We present a lunar resource prospecting and utilization roadmap that showcases how power generation for a lunar outpost could enable Cislunar permanence. This roadmap leverages studies performed through both the Novel Orbital and Moon Manufacturing Materials and Mass Efficient Design (NOM4D) and the Lunar Surface Innovation Consortium (LSIC) to show how efficient lunar permanence is facilitated by extraction of lunar resources combined with manufacturing and fabrication of large precise structures, such as solar arrays, through NOM4D.

Previous Work: Most exploration plans of the lunar surface (the NASA-led Artemis Program) target the South Polar Region, because there is persistent sunlight, volatile ices, and the Moon's mineralogical resources (anorthositic highlands regolith). Therefore, any early civil or commercial lunar raw material stockpiling depot would likely be located in this region. Previous NOM4D studies [1] have shown that large (~1 km^2) NOM4D-fabricated solar arrays, assembled on-orbit and wirelessly providing 1 MW of power to the lunar surface, could enable extreme lunar prospecting and production of highlands regolith into oxygen, silicon, and aluminum, supporting the fabrication of ~38,000 additional, residential sized, solar panels equating to ~11 MW of output power. These results built upon LSIC's In-Situ Resource Utilization Systems Integration Study [2], which estimates the power budget for regolith excavation and the extraction of critical resources. In the LSIC study, a molten regolith electrolysis (MRE) reactor is assumed to produce 10 metric tons (tonnes) of oxygen (O_2) per year from electrolyzing molten lunar highlands regolith, consisting of anorthite ($CaAl_2Si_2O_8$), and ilmenite ($FeTiO_3$). The byproducts of the MRE process are 10 tonnes of iron, 20 tonnes of aluminum, and 49 tonnes of silicon, which are valuable raw materials.

Current Objectives: In this study, we expand upon the above work to perform an identification and analysis of lunar-based design reference missions that demonstrate end-to-end requirements and dependencies of technologies complementary to the manufacturing of large precise structures (i.e. solar arrays, optical and radio frequency (RF) antenna) currently investigated by NOM4D [3,4]. The Lunar-based design reference missions investigated here investigate applications of lunar-sourced materials and manufacturing that primarily leverage structural materials, with an eye towards other necessary manufactured products and applications such as propellant and infrastructure development. This analysis demonstrates the significant set of capabilities and operational utility that NOM4D-enabled manufacturing could support.

Acknowledgements: This material is based upon work supported by the Defense Advanced Research Projects Agency under Contract No. HR0011-22-D-0001/ Task Order HR001123F0002. The views and conclusions contained in this document are those of the author and should not be interpreted as representing the official policies, either expressly or implied, of the Defense Advanced Research Projects Agency or the U.S. Government.

References:

[1] DeCoster, M.E., et al. (2022), *Cislunar Security Conference*. [2] Berdis, J., et al. (2021), LSIC Surface Power Report. [3] DeCoster, M.E., et al. (2023), AIAA SciTech Forum. [4] P. Campbell, (2022), JHU-APL Press Release, https://www.jhuapl.edu/PressRelease/220323-darpa-apl-enabling-structures-on-orbit-moon

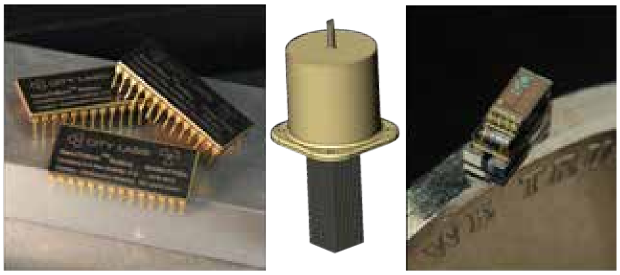
Tritium-Based Power, Heat Sources, and Sensors for the Lunar Surface.

P. Cabauy[1], J. Grant[1], R. Cabauy[1], J. Hernandez[1], M. Stone[1], and T. E. Adams[2], [1]City Labs Inc. 12217 SW 131st Ave, Miami, FL 33186. [2]Purdue University, 401 N. Grant St., West Lafayette, IN 47907. Peter.Cabauy@citylabs.net

Introduction: Maintaining a sustained presence on the lunar surface poses a significant challenge for platforms that require continuous nanowatt to milliwatt power for decades. This power range can enable a wide range of applications from micro-computing mote sensors to thermoelectric power converters. Power availability, and the potential for power sources to meet the demands of extreme environment, can dictate platform operational capabilities that limit the mission persistence. Radioisotope power sources provide a compelling alternative to conventional power sources for operation in extremes of temperature, pressure, and without requirement for illumination, or complications common with chemical batteries [1]. These capabilities can enable extended missions in the extreme cold and dark regions of the lunar surface such as craters while also remaining operational in extreme hot temperatures and direct sunlight.

City Labs' NRC general licensed NanoTritium™ betavoltaic has been demonstrated to be safe, to provide continuous power for over 15 years, and to operate in extreme temperature (-55°C to 150°C) without permanent energy loss or damage [2] and is available for purchase. The power sources can operate beyond these temperature extremes for even more demanding applications. The Defense Science Board have identified Betavoltaics as a disruptive technology that DOD and NASA should pursue, and now, the technology is being developed for space applications [3]. Combinations of radioisotope direct and indirect conversion technologies are identified by NASA as potential power sources in lunar missions [4] and the ESA is investing heavily in radioisotope power sources for upcoming missions [5].

Advances in Tritium-based Power and Heat Sources: Recent work in material development, experiments, modeling [6], designs, tritium thermoelectrics, and proposed advances will be presented and discussed [1], [7], [8]. An overview of City Labs' current projects and improved capabilities to domestically manufacture tritium-based power and heat sources will lead to unique solutions to support challenging lunar surface missions. City Labs is developing and implementing a domestic tritium-loading manifold for joint use in producing its commercial betavoltaic power sources as well as in R&D applications for internal and external projects. A discussion about tritium betavoltaic powered wireless mote sensors for space applications is presented. The tritium loading manifold has a 20-bar pressure capability and -210 ˚C to 600 ˚C temperature capability. The loading manifold is expected to be operational and available for development projects in Q3 2023.



References:

[1] C. Zhou *et al.*, "Review—Betavoltaic Cell: The Past, Present, and Future," *ECS J. Solid State Sci. Technol.*, vol. 10, no. 2, p. 027005, 2021, doi: 10.1149/2162-8777/abe423. [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. [3] T. R. Alam, M. T. Tchouaso, and M. A. Prelas, "Summary of the design principles of betavoltaics and space applications," *Photovoltaics Sp.*, pp. 293–345, Jan. 2023, doi: 10.1016/B978-0-12-823300-9.00003-0. [4] T. W. Kerslake, "Electric Power System Technology Options for Lunar Surface Missions," *NASA Tech. Reports*, no. April, 2005. [5] E. Gibney, "How nuclear waste will help spacecraft explore the Moon — and beyond," *Nature*, vol. 612, no. 7940, pp. 385–386, Dec. 2022, doi: 10.1038/d41586-022-04247-6. [6] T. E. Adams, S. T. Revankar, D. S. Cheu, P. Cabauy, J. Grant, and B. Elkind, "Experimental and Modeling Research on Leading Betavoltaic Technology," Jul. 2018, doi: 10.1115/ICONE26-82475. [7] T. E. Adams and W. Lafayette, "ICONE26-82475," pp. 1–8, 2018. [8] T. Adams, S. Revankar, D. Cheu, P. Cabauy, and B. Elkind, "High Energy Density Applications," pp. 215–218, 2016.

LANDO: Developing Autonomous Payload Offloading Capabilities for Lunar Surface Operations

J.E. Cline[1], W.J. Waltz, D.R. Bisio, I.M. Wong, T.J. Scott, S. Close-arzon, J.N. Moser, and J.S. Friz, [1]NASA Langley Research Center, Hampton, VA, 23666 (Contact: julia.e.cline@nasa.gov)

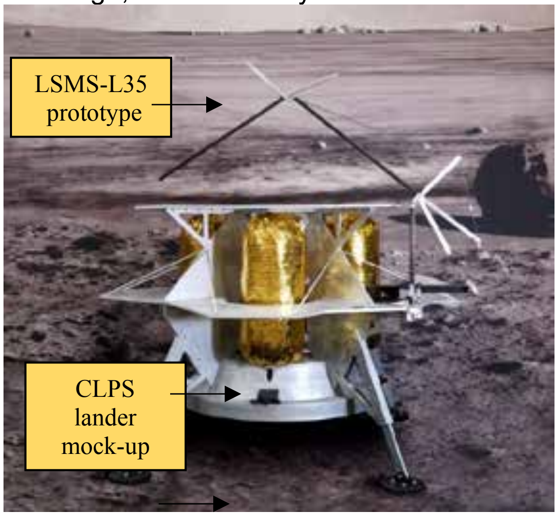
Introduction: The Lightweight Surface Manipulation System (LSMS) AutoNomy capabilities Development for surface Operations and construction (LANDO) [1] project is an Early Career Initiative selected for funding by NASA Space Technology Mission Directorate. LANDO is developing a general-purpose autonomy framework applicable to serial and tension-actuated manipulation agents, that will be validated using an existing prototype of the LSMS-L35 (35-kg wrist lift capacity on the lunar surface [Fig. 1], sized for a Commercial Lunar Payload Services (CLPS) mission). The autonomous LSMS-L35 will be used to demonstrate autonomous payload handling capabilities for Lunar and other planetary surfaces, directly addressing STMD capability gaps in autonomous excavation and construction operations, advanced robotics and spacecraft autonomy technologies, and technologies supporting emerging space industries including the In-Space Servicing, Assembly and Manufacturing national strategy [2].

LSMS: The LSMS is a tension actuated robotic agent that is scalable (reach and lifting capacity in different gravity environments), versatile (types of surface operations), and reusable. Compared to serial arms, the LSMS provides significantly higher structural efficiency and mechanical advantage, enabling a greater payload lift capacity at a lower system mass. The LSMS is envisioned to be a crucial part of the excavation and construction portfolio, capable of supporting a variety of activities on the lunar surface.

Autonomous payload handling is one of the first activities the LSMS can support that develops capabilities that are extensible to other surface operations. Payload handling is required to: remove payloads from a lander; place payloads on mobile agents for transport from a lander to construction site/assembly point; emplace payloads in their operational configuration, and aggregate components to create an asset. As an example of this critical gap, manifested CLPS missions do not currently have a ubiquitous payload offloading capability; payloads (excluding rovers) are designed to remain on the lander.

Why Autonomy? Autonomous robotic systems capable of carrying out excavation and construction operations are a fundamental and critical capability required for realizing the NASA Artemis program vision to "emplace and build the infrastructure, systems, and robotic missions that can enable a sustained lunar surface presence [2]." While teleoperation is still feasible for lunar surface operations, increased latency at Mars will require validated supervised autonomous technologies capable of operating with minimal human involvement (human-on-the-loop) unless an unexpected event occurs requiring human intervention. Autonomy reduces operator burden, allows operations to continue during uncrewed periods, increases the safety of operations by automatically detecting and handling faults, and allows operating in high latency environments.

Development Activities: LANDO is extending critical autonomous operations to the manipulation domain and creating an integrated system, based on reusable software modules, that is capable of planning and executing payload handling and autonomous surface operations without requiring human intervention beyond a supervisory role. The priority features under development are 1) autonomously offload payloads from a tilted lander deck without buckling the LSMS; 2) sensing whether a payload is safe to lift and handle; and 3) integrate with Astrobotic's CLPS lander. The poster presentation will highlight current development activities over the past year on LSMS-L35 prototype hardware design, and autonomy software.



References: [1] Cline, J.E. et al. (2022) *AIAA SciTech Forum* [2] In-Space Servicing, Assembly and Manufacturing National Strategy, retrieved: January 13, 2023. [3] NASA's Plan for Sustained Lunar Exploration and Development," retrieved: 6 January 2023.

HBCU – Led International Research Collaboration on Solar in Space. Shamara Collins, PhD[1] and Richard Damoah, PhD[2], [1]The Futures Forum, Silver Spring, Maryland, [2]Morgan State University, Baltimore, MD. (Contact: shamara.collins@thefuturesforum.org)

Introduction: Sustained presence of human beings on the lunar surface requires inclusion of all "races" or ethnicities [1]. Quality of life relies on the access to power for things like security, communications, heating, and food. It is critical that the earth-bond disparity of electricity access is not duplicated in space [2]. Solar photovoltaic (PV) systems are an established solution to address most power needs, but the technology has lingering remote deployment issues and inefficient energy conversion rates. The Clean Energy Space Research International Collaboration (CESRIC) has a dynamic approach to address the lunar surface power needs.

Methods: The multi-pronged approach prioritizes the use of perovskite (PVSK) cells in both terrestrial and lunar surface application. The effectiveness of this technology was measured under different environmental conditions in both the Northern and Southern hemispheres. The variables considered represent parameters likely found in space (i.e. temperature, humidity, air quality, solar irradiance, and power output).

The CESRIC Project Academic Institutions:

1. Morgan State University (MSU) (USA)
2. University of Oulu (Finland)
3. Norther Caribbean University (Jamaica)
4. University of Mauritius (Mauritius)
5. Charles Darwin University (Australia)

The research focused on lab scale PVSK solar cells provided by Dartmouth Engineering (Thayer School) in New Hampshire, USA. These types of solar cells are poised for space missions because of their power to weight ratio, flexible materials, and radiation tolerance [3]. The innovation depends on the fabrication technique which pairs high-speed flexographic printing with rapidly annealed sol-gel inks [4]. To further simulate lunar surface conditions, remote access was an added variable. Essentially, the setup was intended to be automated using minimal manual interaction with equipment and cloud-based data collection.

Discussion: The ongoing research project has proven successful for two main reasons. Technically, the perovskite solar cell fabrication method addresses glaring manufacturing concerns. Bottleneck issues about the scale and replication of PVSK are being addressed by the gel printing technique. The experimental setup is well designed to explore the devices sensitivity to moisture because of each location's unique weather pattern. The improved fabrication method is intended to be compact and energy efficient, supporting long term strategies to manufacture PVSK modules on-demand at the Lunar Settlements. The team met a lot of challenges when searching PVSK products in the marketplace ecosystem, highlighting a deficit in the solar industry, further justifying the need for funding in this area.

The project is a great demonstration of international collaboration across institution types. MSU is one of the first Historically Black Colleges and Universities (HBCU) in the country to lead and host this sort of research initiative. MSU serves as the 'command center' for the research team. It is fitting that the lead institution represents communities with environmental injustices and others are in areas which lack energy access. Quality project management addressed logistical issues with scheduling across time zones and organizations, but customs delays and supply chain issues were uncontrollable. Some Information Technology (IT) challenges persist, denoting an area of interest for universities to support international collaborative and cloud-based research. A single platform of equipment to match the research specifications was unattainable. Most weather stations built for meteorological parameters do not consider measurements for solar technology. Therefore, more funding is needed to address challenges with academic research whether it be IT infrastructure issues or comprehensive measurement equipment readily available in the marketplace.

References:

[1] The American Journal of Human Genetics (2018) *AJHG, 103,* 636– 636. [2] IEA (2022) *World Book Energy Outlook*. [3] McMillon-Brown, L. et al (2022) *ACS Energy Letter*, 7, 1040–1042. [4] Huddy, J. et al (2022) *Advanced Materials Technologies, 7, 2101282*.

Development of New Lunar Highland Regolith Simulant, NUW-LHT-5M.

M. J. Creedon[1] ,T. Linneman[2], D. L. Rickman[3], Michael Effinger[4], [1],[2]Washington Mills Electro Minerals (Washington Mills Electro Minerals, 1801 Buffalo Ave., Niagara Falls, NY, 14303, mcreedon@washingtonmills.com, tlinneman@washingtonmills.com) [3]Jacobs (Jacobs Space Exploration Group/NASA Marshall Space Flight Center, Huntsville, AL, 35812, douglas.l.rickman@nasa.gov) [4]NASA (NASA Marshall Space Flight Center, Huntsville, AL 35812, michael.r.effinger@nasa.gov)

Introduction: NASA has a need for large quantities of lunar simulants that closely match future manned lunar missions at landing sites near the Lunar South Pole. The current simulant was designed to approximate NU-LHT-2M, and -4M, except using natural minerals and a fully synthetic, non-basaltic, high calcium glass.

Washington Mills in Niagara Falls, NY was contracted to produce this new simulant due to their electric arc furnace (EAF) fusion technology and capabilities for crushing and sizing ceramics.

The primary objectives of this work were: (1) to create a commercially produced simulant that contains a high fidelity, high calcium (An90+), low Mg/Fe glass without basaltic constituents; (2) to create a simulant that uses existing, terrestrially mined, and readily available minerals blended with a synthetic glass, and (3) accomplish objectives (1) and (2) using conventional processing methods capable of production levels that can meet substantial current and future demands of NASA projects. Another consideration was that highland simulants closest to meeting these requirements, NU-LHT-2M and -4M types, are out of production and largely out of stock.

Design: The design chosen for development and production for this work is NU-LHT-2M, designed by Doug Stoeser and Douglas Rickman, which uses Stillwater anorthosite and norite rocks and synthetic glass. The composition targeted the average composition, glass content and particle size distribution of Apollo 16 samples [1]. The design utilizes two Stillwater minerals, anorthosite (37.7 wt.%), norite (17.6 wt.%), a commercially sourced olivine (4.7 wt.%), and a synthetic glass (40 wt.%).

Processing: Stillwater rocks were hand collected and initially crushed by the USGS. Further crushing and milling was performed at Washington Mills.

For the glass, oxides were blended in the appropriate ratios, blended in a v-blender, and placed in a graphite lined, water cooled pot. The mixture was fused in Washington Mills' pilot scale, 500 kW EAF. The molten glass was then poured into water and quenched to inhibit crystallization. Several pour/quench cycles were required to produce the total quantity of glass needed.

Anorthosite, norite and olivine were milled together to the target particle size in a ball mill. The glass was ball milled separately. The complete simulant was produced by blending the milled materials. Particle size distribution, phase and chemical analyses of the materials was were performed at Washington Mills.

Results: The glass composition was found to match the Apollo 16 oxide content average [1] quite well, with the exception of SiO_2 and Fe_2O_3. The deviation of SiO_2 and $Fe_2O_3$from batched content was believed to be due to limitations inherent in the use of the arc furnace technique for these types of materials. A particle size distribution of the full simulant formulation closely matching the average for the Apollo 16 samples was also achieved. Fig. 1 shows the morphology of the final simulant particles. The size distribution is compared to the target in Fig. 2.

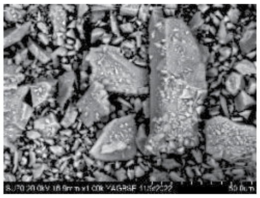


Figure 1. Particle morphology of milled simulant

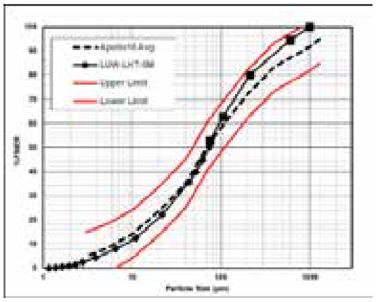


Figure 2. Size distribution of simulant.

Conclusions: A new lunar highlands type simulant containing a high-quality synthetic glass, closely matching an average composition of the Apollo 16 regolith was produced. Processing utilized easily scalable mineral and glass making methods.

References: [1] Stoeser et al. (2010) "Design and Specifications for the Highland Regolith

Filtration and Collection of Lunar Dust.

Vijay V. Devarakonda[1] and Michael D. Hogue[1], [1]Analytical Scientific Products LLC, 4616 Willow Ln., Dallas, TX 75244. (Contact: vijay@analyticalscientificproducts.com)

Dust from various sources such as the particles generated by the cabin crew and the external dust brought into the cabin after extra vehicular activity can compromise the indoor air quality in spacecraft during future Lunar missions. In addition, the dust particles have the potential to foul mechanisms, alter thermal properties, and obscure optical systems. Therefore, there is an urgent need for the development of technologies to remove, manage, and monitor aerosolized particulates and dust intrusion into the pressurized habitable volumes and compartments in crewed spacecraft systems.

Through a Phase I SBIR project funded by the NASA GRC, Analytical Scientific Products LLC (ASP) developed an innovative device to separate and collect dust particles from spacecraft cabin air and airlock compartments. The ASP device uses a combination of electrostatic and electrodynamic fields to charge and remove the dust particles from air and collect them in a reusable bag. This device takes in the dust-laden air from the cabin and releases particle-free clean air that can be used in downstream equipment like the cabin air revitalization system. Our device is compact, lightweight, and energy efficient. It is equally effective in filtering both the dust particles generated by the crew inside the spacecraft and those that enter the spacecraft from outside due to extra vehicular activities. This device has no moving parts, and since it does not use filtration media the dust particles do not collect inside the filter minimizing the need for periodic maintenance. It is scalable and can be sized to handle various gas flow rates and dust loadings and can clean both the cabin and the airlock compartments.

As a part of the SBIR project, we have designed and constructed a breadboard version of this device, as well as an instrumented test apparatus to evaluate its performance. We equipped the test apparatus with a blower to generate the high-speed air flow, an aerosolizer to disperse the dust particles into the air flow, a duct to transport the dust aerosol into the filter and optical instrumentation to measure the concentrations of dust in the contaminated air stream that enters the filter and the particle-free clean air stream that exits the filter. We performed a series of tests with two morphological Lunar dust simulants varying the voltages applied to the filter. Sample dust concentration versus time data at the filter entrance and the exit from one of these tests are presented in the figure below. These data clearly show that the concentration of dust decreases dramatically across the filter. We calculated a dust filtration efficiency of 96.2% in this test. The design of the test apparatus and the results from more than 25 dust filtration tests are presented in detail in this paper.

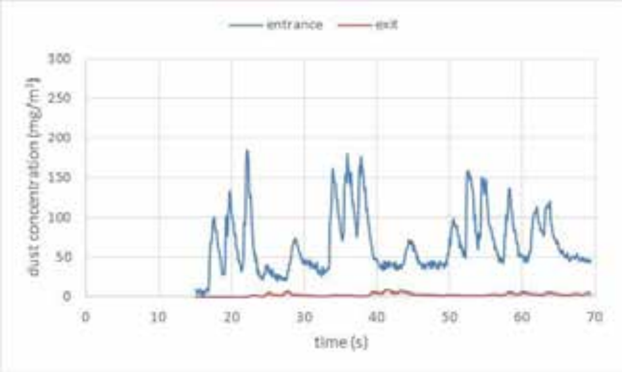


Figure 1: Dust concentrations in the air streams that enter and exit the filter in test #L07 with ASP's Lunar dust filtration and collection device.

Integrating Thermal Processing of Lunar Ice and Solid Oxide Electrolysis (SOXE) for H_2 and O_2 Production.

D. Dickson[1], N. Emadi[1], J. Schmit[2], J. Schmidt[1], C. Dreyer[1], G. Jackson[1], M. Hollist[3], D. Larsen[3], P. Czernichowski[3], M. Wilson[3], A. Yarosh[4], and J. Hartvigsen[3]. [1]Colorado School of Mines, 1500 W Illinois St, Golden, CO, 80401, [2]Lunar Outpost, Inc., 2830 East College Avenue, #106, Boulder, CO, 80303. [3]OxEon Energy LLC, 257 River Bend Way, North Salt Lake, UT 84054. [4]Northrop Grumman, 2000 W NASA Blvd Melbourne, FL 32904. (Contact: ddickson@mines.edu)

Introduction: A major NASA in-situ resource utilization (ISRU) technology development goal for the coming years is to develop more energy-efficient systems for splitting lunar-derived water into H_2 and O_2 in a Moon-relevant environment. An excellent candidate technology for this purpose is high-temperature ($T > 700℃$) solid oxide electrolysis (SOXE), which, with well designed balance-of-plant (BOP), requires lower specific energy (kWh_{elec}/kg_{H2}) than current alkaline or proton electrolyte membrane electrolysis in energy efficiency [1]. To this end, OxEon Energy LLC and Colorado School of Mines designed, fabricated, and tested an integrated SOXE stack and BOP, in a lunar-relevant environment of a large cryovac chamber.

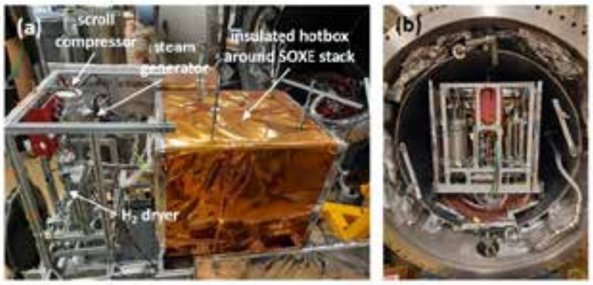


Fig. 1. a) Lab-scale electrolysis system. b) BOP and SOXE stack hotbox inserted into the vacuum chamber with the main door open before testing.

Experimental Setup: The SOXE stack comprised 62 cells of stabilized zirconia electrolyte between nickel cermet cathodes and manganite Perovskite anodes. This stack was covered on all sides by an insulative hotbox [2]. The BOP consisted of two custom-built shell-and-tube recuperator (one each for the H_2 and O_2 exhaust, each of which exchanged heat with incoming steam), a steam compressor, a heater-containing tank steam generator (which also further exchanged heat with the outgoing O_2 exhaust), and a counterflow "H_2 dryer" heat exchanger which cooled the H_2 exhaust, preheated incoming liquid water for the steam generator, and collected the condensate from the excess steam pulled from the H_2 exhaust. Both systems were optimized [3], fabricated and tested separately, and then integrated together.

The integrated SOXE stack and BOP were installed in the Mines Center for Space Resources (CSR) cryo-vac chamber, along with their requisite control, power, and fluid feedthroughs. The chamber was pumped down to single-digit torr pressures and -80ºC to approach lunar permanently-shadowed region (PSR) conditions. Fig. 1a shows the integrated lab-scale system, and Fig. 1b shows the system inserted into the test vacuum chamber.

Results: As shown in Fig. 2, the final test on June 29, 2022 demonstrated H_2 production of >1.8 kg_{H2}/day and total power consumption (by stack, compressor, heat trace, and steam generator heater, namely) of < 50 kWh_{elec}/kg_{H2}, surpassing the project's Key Performance Parameters (KPPs) and advancing the technology to a technology readiness level (TRL) of 5, an important milestone. Future work will focus on advancing the technology's TRL to 6 and beyond and moving it, and lunar ISRU, toward flight status.

Fig. 2. Graph of SOXE H_2 production and energy usage during final test, as compared to targeted performance thresholds. The yellow line shows the specific energy performance threshold, and the red line the H_2 production rate threshold.

References: [1] S. O. et al. (2017), *IJHE*, 42(52), 30470-30492. [2] J. H., et al. (2021), *ECS Meeting Abstracts* (1, pg. 194). [3] D. D. et al. (2021). *IEEE Aerospace,* Abstract #50100.

Regolith Derived Materials and Structures through Microwave Casting (DARPA NOM4D).

S.L. dos Santos e Lucato[1], J. Davis[1], J. Berger[2] and R.M. McMeeking[2], [1]Teledyne Scientific, 1049 Camino dos Rios, Thousand Oaks, CA 91360, [2]University of California, Santa Barbara, Dept. of Mechanical Engineering, Santa Barbara CA 93106. (Contact: sergio.lucato@teledyne.com)

Introduction: One goal of the DARPA NOM4D program was to develop methods to convert raw lunar regolith into structural materials for large orbital platforms. Microwave casting is an energy efficient method and compatible with lunar surface operation. We have demonstrated the process to cast dense structural materials from various sources while tailoring the materials properties through limited amount of additives. The materials were subsequently used to build a thermal invariant truss structure.

Program Premise: The project had two primary objectives. First, to develop a process to convert raw regolith into dense materials suitable to construct large orbital structures, the design of which was the second objective. The key restriction was the limitation to include no more than 5 wt% of materials brought from earth. The notional structures were prescribed as up 100 m in diameter with a precision (maximum deflection between any two points) of ≤ 1 mm.

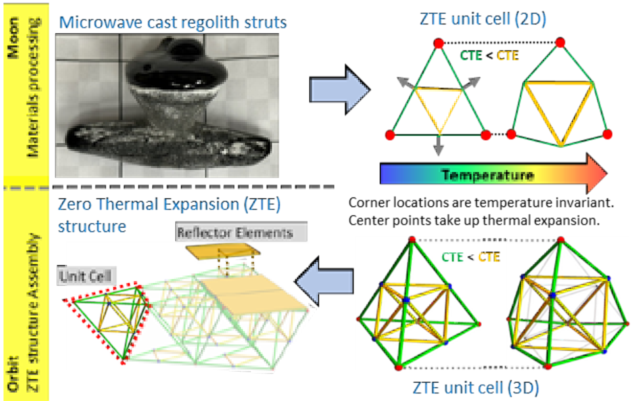


Figure 1: Program concept from cast regolith units to full zero thermal expansion (ZTE) structure.

Microwave Casting: Microwave casting was chosen as it is energy efficient and compatible with operation on the lunar surface with minimal adaptions. Other methods, such as sintering or additive manufacturing, were not considered due to production rate limitations.

The conversion process had to overcome two obstacles. Raw regolith is not by itself microwave susceptible, i.e. it will not efficiently heat in a microwave field. This was solved through a utilization of a highly susceptible crucible material into which the regolith is deposited. Heating rates of > 100°C/min are easily achievable in this configuration. The second obstacle was related to the requirement of being able to modify the coefficient of thermal expansion (CTE), melting point, viscosity and crystallinity with only limited amounts of additives. Terrestrial glass processing informed the selection of various additives. A test matrix was run to develop a database of additives and their effect on the aforementioned properties. Large CTE modifications were of particular interest for the structures of interest.

The program successfully demonstrated a process to convert pure regolith simulant into dense materials with a wide range of properties. The structural materials created exhibited flexural strengths > 80 MPa, elastic modulus of 80 GPa and densities of 2.5 g/cc. Various other materials, such as a low-density foam, were generated as well with potential uses in other lunar applications.

Thermally Invariant Structures: The second aspect of the program was to design a high-precision structure fabricable from the generated regolith derived materials. The Zero Thermal Expansion (ZTE) concept [1] achieves that goal by using two materials with a CTE ratio of at least 2:1 in a stretch dominated truss structure. Material pairs with this ratio have been successfully demonstrated in this program. The higher CTE material counters the thermal expansion of the lower CTE material while maintaining high stiffness to weight ratio. Performance models created in the program indicate that large orbital structures of 100 m diameter can achieve a precision of better than 1 mm between any two points subjected to vibration, acceleration and thermal variations. It could also be shown that the effective CTE of the unit cell remains near zero even though the CTE of the individual materials vary slightly with temperature.

References: [1] C.A. Steeves, S.L. dos Santos e Lucato, J.W. Hutchinson, A.G. Evans, "Concepts for structurally robust materials that combine low thermal expansion with high stiffness", *J. Mech. Phys. Sol.*, 55 [9] 1803-1822 (2007).

Automated Site Preparation - ASPECT.

C. B. Dreyer[1], A. J. Petruska[1], N. T. Dantam[1], J. Rostami[1], K. M. Cannon[1], G. F. Sowers[1], D. Johnson[1], D. P. Purcell[1], D. Hammer[1], K. Spevak[1], C. Okwor[1], R. Banerjee[1], P. J. van Susante[2], C. Carey[2], AJ Gemer[3], J. Kendrick[3], J. Cyrus[3], and A. Esbeck[4], [1]Colorado School of Mines, 1600 Illinois St., Golden Colorado, 80401, [2]Michigan Technological University, 1400 Townsend Drive, Houghton, MI 49931, [3]Lunar Outpost, 12650 W. 54th, Arvada, CO 80002, [4]Bechtel, USA. (Contact: cdreyer@mines.edu)

Introduction: The lunar surface is marred by impact craters and rocks over a wide range of length scales. Lunar landing pads are anticipated to be up to 200 m in diameter, which will contain hundreds of craters of 2 m diameter and less and hundreds of rocks. The first step in building a landing pad on the lunar surface will be to clear, level, and compact the surface. Landing pads are an infrastructure element expected to support human exploration of the Moon [1]. The Autonomous Site Preparation: Excavation, Compaction, and Testing (ASPECT) project is a NASA LuSTR [2] funded project to demonstrate site preparation of the lunar surface for the construction of a lunar landing pads.

Approach: The ASPECT project consists of a team of lunar technology experts, roboticists, and computer scientists from several institutions. A mobility platform based on the Lunar Outpost Hound vehicle will be light-weighted and a dozer blade added by Mines with a compaction system from MTU. Mines also provides sensing and autonomy/planning. Tests will be conducted at a 10 m diameter site managed by Mines.

Concept of Operations: CONOPS begins with a survey of the site and assessment of the deviation of the site from the site preparation requirements (Figure 1). Next, task and motion planning algorithms formulate a plan. Possible tasks include Move Rocks, Move Regolith, Compact Surface, Charge, and Smooth Surface. Control and state estimation limits may require local replanning. When the local motion plan is complete site preparedness is surveyed and the process repeats.

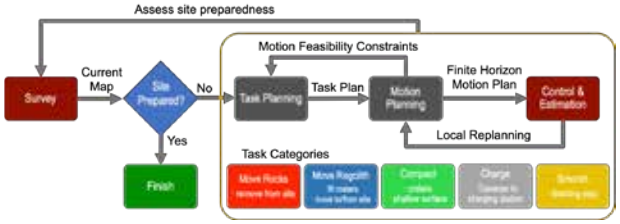


Figure 1: ASPECT CONOPS.

Mobility Platform: The ASPECT mobility platform is based on a Lunar Outpost HOUND, Figure 2. To simulate lunar gravity while tests are conducted in 1-g, HOUND is light weighted. The system, including regolith/rock manipulation, sensing, and compaction has a not to exceed mass of 83 kg, which simulates a 500 kg vehicle on the Moon.

Figure 2: Lunar Outpost HOUND (left) and ASPECT concept (right).

Regolith and Rock Manipulation: A multi-function dozer blade pushes and/or lifts regolith and rocks. In principle, to limit pushing forces only low-density regolith is manipulated. Wheel grousers or rippers on the back of the blade are used to tear the surface if necessary. The wheels and dozer blade are designed together to ensure the vehicle can push a fully loaded blade. Forces and wheel slip are carefully managed during operation. Back blading is used to smooth the surface as the finishing step to 1 cm RMS.

Compaction: The regolith is to be compacted to 90% relative density using a series of pins pressed into the surface aided with a pressure plate. Vibration of the pins cause the regolith to compact, and pins automatically retract as the compaction state achieves the desired compaction level. The required pressure applied by the plate and vehicle mass limit the area that can be compacted per placement of the system. Full site compaction is achieved by repeated placements.

Conclusions: We have presented the in-progress ASPECT project plan. In the coming months, detailed designs, supporting tests and analysis will be completed.

Acknowledgements: This work was supported by a Lunar Surface Technology Research grant from NASA's Space Technology Research Grants Program

References: [1] NASA, "Artemis Plan: NASA's Lunar Exploration Program Overview," 2020. [Online] https://www.nasa.gov/sites/default/files/atoms/files/artemis_plan-20200921.pdf.
[2] NASA, "Lunar Surface Technology Research (LuSTR) 2021," [Online]. https://www.nasa.gov/directorates/spacetech/strg/lustr/2021/

Space Urban Planning: Addressing a Significant Technology Gap in Planning for Infrastructure and Sustained Human Settlement on the Lunar Surface.

Britt Duffy Adkins[1], [1]Celestial Citizen, Pasadena, CA, britt@celestialcitizen.com.

Introduction: In the coming decades, there will be an exponential increase in commercial and governmental activity on the lunar surface, and this uptick in operations will increase the complexity of mission planning. As a result, lunar surface operations will need an integrative planning process and approach that focuses on long-term objectives in addition to short-term realities. In order to bring about a greater degree of order, collaboration, and build consensus among stakeholders, a new cross-discipline focus area of space urban planning is required.

Space Urban Planning: This emerging and critical focus area will act as a transdisciplinary approach to designing off-Earth built environments and infrastructure, as well as, the development of the social, political, and economic underpinnings that will allow a future sustained human settlement to thrive. Through the integration of public participation, policymaking, cross-industry initiatives, systems thinking, and technology integration, space urban planning allows for community-driven visioning and consensus-building around policies and norms in space and specifically on the lunar surface. In many ways, space urban planning asks the question - how does humanity scale?

Lunar Urban Planning: In order to develop a sustained human presence on the Moon, lunar urban planning will be required as a framework for decisionmaking, large-scale systems thinking, governance, process planning, and lunar community building. As MIT city planner Kevin Lynch aptly wrote: “Since an unstable ecology risks disaster as well as enrichment, flexibility is important, and also the ability to learn and adapt rapidly [1].” So naturally, if we begin integrating this mindset into the early stages of all future lunar suface mission planning then we might avoid the costly, ineffective, and unproductive sprawl that defines too many terrestrial cities. The need for urban planning in space is critical from even the earliest stages of development because the stakes are higher in an environment that is harsh, unforgiving, and does not allow for even the limited reset that Earth cities might provide. When considering the cost of doing anything in space, it would be wise to consider the cost of undoing anything in space.

Approach: A critical component of lunar urban planning is going to be a commitment to continued public outreach and integration of feedback into all future planning of space missions and eventual space communities. Utilizing the full array of the urban planning toolkit and process to engage and excite the public about the future of a human settlement on the Moon, this gathered public feedback and community-driven data must then be integrated alongside expert opinions, academic and industry research, mission operations, and technology development to begin building the foundations of a lunar comprehensive planning document. Present technologies in both the urban planning and space-related fields can be used to scale this effort, as well as, support the robust research required for such a study. It will also be essential to plan and guide a process that leverages the talented space architecture and lunar construction communities, to be key parties involved in taking community-led vision and converting it into feasible and structurally-sound designs. A significant portion of this work will also be policy-driven and involve the political and economic factors that must also be discussed and planned for in order to actualize a lunar community that is sustainable in the long-term.

Celestial Citizen: Celestial Citizen is currently building a company and team that will work to integrate these various components, connect stakeholders, provide linkages to relevant industry and expertise outside of the space sector, and provide strategic analysis in the delivery of a comprehensive plan for a sustained human presence on the lunar surface.

Closing: As Professor Carlo Ratti of MIT points out, “planning decisions we make today determine the scope of choices we will have tomorrow [2].” Establishing a new focus area of space urban planning applied to the lunar surface will support a greater scope of choices for humanity’s future on the Moon and beyond – advancing the likelihood of a thriving, sustained off-Earth human presence.

References: [1] Lynch, Kevin. (1984). *Good City Form.* The MIT Press. [2] Ratti, Carlo and Matthew Claudel. (2016). *The City of Tomorrow: Sensors, Networks, Hackers, and the Future of Urban Life.* Yale University Press.

Resilient Design Strategies for Smart Space Habitats. S.J. Dyke[1] K. Marais[2] I. Bilionis[1] J. Werfel[3] and A. Bazzi[4], [1]School of Mechanical Engineering, Purdue University, 585 Purdue Mall, West Lafayette 47907, [2]School of Aeronautical and Astronautical Engineering, Purdue University, ARMS 2041, 701 W. Stadium Ave., West Lafayette 47907, [3]John A. Paulson School of Engineering and Applied Sciences, Harvard University, 150 Western Avenue, Boston, 02134, [4]Department of Electrical Engineering, University of Connecticut, 261 Glenbrook Road, Storrs, 06269. (Contact: sdyke@purdue.edu)

Introduction: SmartHabs are space habitats that have autonomous abilities to *sense, anticipate and respond,* under a variety of manned and unmanned configurations. The Resilient ExtraTerrestrial Habitats Institute (RETHi) is a NASA Space Technology Research Institute that is focused on developing the techniques and technologies for resilient design of Lunar habitats.

Resilient systems must have the ability to survive and recover from a wide range of disruptions. Disruptions are inevitable, and deep space habitats must be resilient to the many hazards that these systems will be exposed to during their lifecycle [1]. Thus, simulations may be helpful for examining their safety, performance and resilience. RETHi is developing new techniques and technologies and studying those through simulation. Two entirely computational simulation environments are being developed to conduct the research of the institute. MCVT is a medium-fidelity model of the key subsystems in a space habitat and their interactions. CDCM is an early-design tool for conducting trade studies to inform the architecture of SmartHabs.

Here we discuss several of the key features of these tools and models needed to carry out quantitative research related to the resilience and autonomous operation of extraterrestrial habitats.

Modular Coupled Virtual Testbed (MCVT): MCVT provides a reconfigurable model of a space habitat system, to enable researchers to critically examine the performance of new techniques and technologies. Our habitat system model includes a core set of subsystems: structural subsystem, regolith shielding layer, power subsystem, and thermal and pressure management systems. The interior of the habitat is modeled as a volume with pressure and thermal properties. Sensors, damage, agents, repair and recovery of the habitat subsystems are included in this system of systems model. The environmental conditions represent the Lunar surface and include a wide range of known disruptions as inputs to the system [1].

The model is developed in Matlab/Simulink and includes capabilities to trigger disruptions as well as the associated consequences, both those that are physics-based (e.g., micrometeorite strikes) and those that are represented in a phenomenological manner (e.g., fire, dust, leakage). Both classes of disruptions can propagate through the system and cause cascading failures. The communication network, data repository and command and control are simulated in a second computer using a Docker container.

To develop our resilient design framework, we needed to model several types of disruptions, damageable and repairable properties, parameterized agent actions, and the ability to start from any set of initial habitat conditions. Because deep space habitats are expected to experience long dormant periods, MCVT is also designed to have the ability to capture transitions between crewed and uncrewed/dormant states.

Control-oriented Dynamic Computational Model (CDCM): Systems of systems involve complex dynamics and interactions among the many subsystems. Choices made during the design of these systems have implications that may be challenging to predict. The CDCM is modular and designed to obtain many realizations of longer-term simulations using models appropriate for that objective [2]. It uses low fidelity subsystem models that depend less on transient behaviors and more on the evolving states of the individual subsystems and of the overall system throughout its lifespan. The emphasis is placed on including the features of the architecture that are most valuable for studying how they impact safety and resilience.

Closing: RETHi has developed computational models of space habitats, which, together with our robotics work and cyberphysical testbed [3], are enabling research needed to establish design principles for resilient and autonomous space habitats.

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

References: [1] Dyke, S.J., Marais, K., Bilionis, I., Werfel, J., Malla, R. (2021). *SPIE Smart Structures & NDE Conf*. [2] Behjat A., et al. (2022) *ASME IDETC*. [3] Maghareh A., Lenjani A., Krishnan M., Dyke S. J., and Bilionis I. (2021). *ASCE Earth & Space Conf*.

Development of A Large Scale Lunar Highlands Regolith Bin at the Exolith Lab. P. Easter[1], L. Weber[1] D. Britt[2] M. Conroy[3], D. Britt[2], and J. Brisset[3]. [1]Exolith Lab, University of Central Florida, Orlando, FL [2]Dept. of Physics, UCF [3]Florida Space Institute. (Contact: parks.easter@ucf.edu)

Introduction: With an increasing interest in the exploration of the Lunar South Pole, there is a growing need for facilities that simulate this environment. Rovers and other hardware planned for use on the Moon require testing on Earth to ensure their functionality, much of which involves the use of regolith simulants. To help further the availability of accurate Lunar testing facilities, the Exolith Lab at the University of Central Florida is building a 100 m^2 regolith bin. This regolith bin will feature a high-fidelity Lunar Highlands Simulant (LHS-2), gravity offloading capabilities, custom terrain options, with a minimum depth of 1 m. It will be available for use by a wide range of customers including: government agencies, private industry, educators, and competitions.

Design: The Exolith bin will have a footprint of 10x10 m and an average depth of 1 m, providing room for both large rover operations and drilling experiments. A 1.2 m retaining wall will contain the ~130 tons of regolith simulant. The regolith bin will be built around a gantry crane that has a 2-ton capacity, allowing vehicles of up to 1 ton to be lifted into the bin and gravity offloaded. The framework of the bin consists of aluminum bars covered by Lexan panels, offering a clear view into the bin with cable pass-throughs and science stations. The frame is fully sealed with a negative pressure dust mitigation system that filters out any lunar simulant dust. This dust once collected is mixed back into the simulant, so that particle size distribution is maintained.

Along the outside of the regolith bin is a walkway that provides operators and other observers with workstations at regolith-level. This will allow teams to set up and operate electronics while having an unobstructed view of operations in the bin. At the corner of the deck is an access room where customers can put on their PPE to enter the bin, as well as clean off after they exit.

Regolith Simulant: One of the most important features of the regolith bin is the regolith simulant within it. While most bins currently in operation are filled with basaltic dust, simulating the Lunar Mare, this bin will be filled with over 130 tons of Lunar Highlands Simulant (LHS-2) that simulates both the mineralogy and geotechnical properties of the Lunar Highlands. This is a key feature, as the Artemis missions are planning to land in the Lunar South Pole, a Lunar highland region. The mineralogy of a regolith drives many of its physical properties, making it important for testing to be done in the right type of regolith simulant.

Terraforming: There are various options to alter the regolith within the bin during use. Due to the 100 m^2 of available surface area, it is possible to reproduce geological structures such as hills, valleys, and craters. Exolith has many of the large rocks that make up the simulants source material, which can also be included within the bin. This is an important feature as it gives rovers and other hardware more accurate terrain to navigate and function within. The ability to create depths greater than 1 m is also essential for the testing of mining operations.

Gravity Offloading: The 2-ton crane within the regolith bin is capable of gravity offloading rovers or other equipment to 1/6th gravity, for a closer representation of Lunar conditions. It is also used to lift heavy equipment into the regolith bin.

Figure 1. Model of Exolith Lab's Regolith Bin

Conclusion: The Exolith regolith bin can provide researchers with the opportunity to test equipment and processes in high-fidelity Lunar Highlands regolith environment. The included features aim to help improve the fidelity of testing and include a variety of options for diverse testing applications.

More information on Exolith's regolith bin is available by request through exolithlab@ucf.edu

LHS-2: A Novel Lunar Highlands Regolith Simulant for Exolith Lab's Regolith Bin. P. Easter[1], A. Metke[1] J. Long-Fox[2], D. Britt[2], and J. Brisset[3]. [1]Exolith Lab, University of Central Florida, Orlando, FL [2]Dept. of Physics, UCF [3]Florida Space Institute. (Contact: parks.easter@ucf.edu)

Introduction: The development of technology for use on the Moon requires facilities for testing both hardware and operational capabilities. With the ever-growing demand for such facilities, the Exolith Lab at the University of Central Florida (UCF) is currently building a large 100 m^2 regolith bin, utilizing approximately 140 tons of high-fidelity lunar highlands regolith simulant. This bin will provide the exploration community with a lunar highlands regolith testing facility capable of gravity offloading large rovers, terrain variations, excavation, and drilling options.

One of the most important aspects of this bin is a regolith simulant that is both mineralogically and geotechnically accurate. To achieve this, a new lunar highlands regolith simulant has been developed at the Exolith Lab that more accurately represents the particle size distribution of regolith found on the Moon. This simulant maintains the mineralogy of Exolith Lab's LHS-1E simulant [1]. This simulant is designated as LHS-2. An accurate particle size distribution is essential for the testing of rovers and other equipment interacting with the regolith, as it determines many geotechnical characteristics of regolith.

Particle Size Distribution: While many simulants focus on maintaining a particle size distribution less than 1 mm, this is not an accurate representation of the actual lunar surface. While it is widely stated that approximately 10% of the lunar regolith is greater than 1 mm [2], this does not provide resolution of size distributions greater than 1 cm**.** The actual percent of lunar highlands regolith greater than 1 mm is between 20-30%, according to the samples returned from Apollo 16 [3]. Considering this, we designed the regolith bin simulant to be coarser, with approximately 26% of the grains greater than 1 mm. This coarse distribution is essential for many of the geotechnical characteristics of the regolith, some of which include Angle of Repose, Shear Strength, and Compaction.

Angle of Repose: It is essential that the particle size distribution of the simulant doesn't compromise any of the other geotechnical characteristics, as they are often just as important for testing. To assure this, Angle of Repose measurements were conducted. These measurements were carried out using the methodology detailed within our previous Angle of Repose study done on LHS-1 [4]. We can see from the values in Table 1 that the Angle of Repose is not compromised by the increased particle size of the simulant, and that it increases slightly from LHS-1 values. The Angle of Repose was done using both a standard mass of 250 g and a small mass of 25 g, to capture the decrease in angle with an increase in mass.

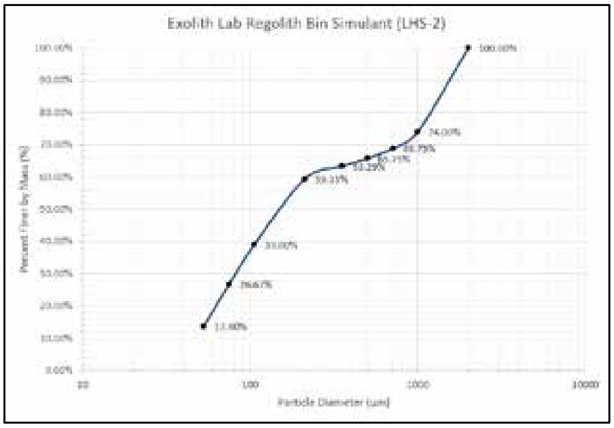


Figure 1. LHS-2 Particle Size Distribution

	LHS-1	LHS-2
25 g Angle of Repose	47.2° ± 2.8°	47.5° ± 1.4°
250 g Angle of Repose	39.5° ± 0.8°	41.6° ± 1.3°

Table 1. Angle of Repose w/ Standard Deviations

Conclusion: This lunar highlands simulant (LHS-2) will give researchers using Exolith Lab's regolith bin increased confidence in their results, as it more accurately simulates the range of particle sizes that will be encountered on the lunar surface. Further tests on this simulant will be carried out in the near future, and this data will be made available to the general public. More information on Exolith Lab's 100 m^2 regolith bin is available by request through exolithlab@ucf.edu.

References: [1] Exolith Lab, LHS-1E Spec Sheet (Dec. 2022) [2] McKay et al. The Lunar Sourcebook (1991), pg. 306 Figure 7.9 [3] Morris et al. Handbook of Lunar Soils (Jul. 1983), pg 432 648 [4] Easter et al. Comparing the Effects of Mineralogy and Particle Size Distribution on the Angle of Repose of Lunar Simulants, LPSC (Apr 2022)

INSTRUMENTING THE ACTIVE REGION IN PHILOLAUS CRATER WITH MOTE LUNAR PENETRATORS

T. Marshall Eubanks[1], W. Paul Blase[1], [1]Space Initiatives Inc , Newport, Virginia 24128 USA; tme@space-initiatives.com;

Introduction: The Space Initiatives "Mote" penetrator is designed to economically deploy instrument arrays on (and in) the lunar surface [1], with an instrument selection including thermometers, accelerometers, geophones and magnetometers [2]. As shown in Figure 1, Motes will burrow into the lunar regolith and come to rest ∼1 meter below the surface, with a tail section remaining on the surface to deploy an antenna mast. Each Mote can also act as a seismic source for the other Motes in sequence, allowing the array of deployed geophones to map subsurface structures with both active and passive seismology. Here, we discuss a proposed deployment of Motes on the floor of the relatively young Philolaus Crater, in order to explore the tectonically active region found there [3].

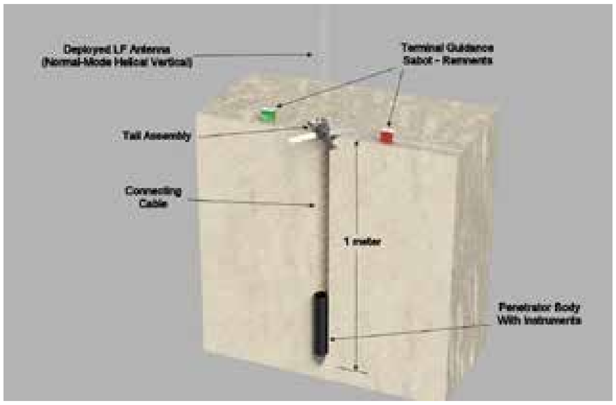


Figure 1: A Mote penetrator after deployment 1 meter into the lunar regolith. The Mote electronics will be below the insulating surface layer of the regolith, and should remain at a constant temperature throughout the entire lunar day.

Deployment in the Tectonicially Active Region in Philolaus Crater: In an extensive search of Northern lunar latitudes we found several apparently tectonically active areas, including a region in the Eastern part of the floor of Philolaus crater with many signs of recent activity. Figure 2 shows an apparently intrusive feature in this region we call the Stegosaurus Dome, at 31° 2' 13.45" W 72° 30' 32.44" N. This feature is adjacent to other domes and an extensive set of intersecting rilles, and is within a few km of a set of candidate lunar skylights [3].

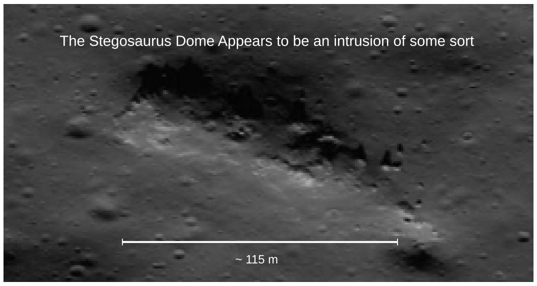


Figure 2: A high resolution image of the "Stegosaurus" Dome, so-called because of the plate-like boulders apparently being shaken or forced from it, from the LRO NAC image M155445584RC. North is at the top.

The Stegosaurus Dome is ∼119 m long and ∼6 m high, and is called that because of the plate-like boulders apparently being shaken or forced from it. A structure like this must be geologically recent, and may be growing or being forced upwards by geologic forces. While this Dome has similarities with volcanic features on Earth, the regolith at these latitudes is fairly cold, and it is conceivable that it is more aqueous than volcanic.

Figure 3 shows how a string of four Motes could be deployed over this tectonically active region, providing information about the surface and subsurface activity at the site. Penetrator deployments such this should be able to determine if this activity is continuing at the present, and also determine something of its subsurface structure.

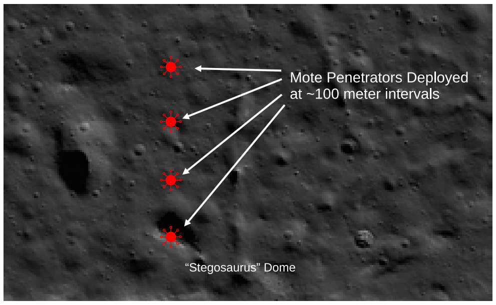


Figure 3: A string of 4 Motes deployed on the Philolaus crater floor, ending with one on the Stegosaurus dome, which appears to be a possible volcanic intrusion. With Mote geophones it should be possible to determine if these domes are still tectonically active.

References: [1] C. J. Ahrens, et al. (2021) *The Planetary Science Journal* 2(1):38 `doi`. [2] T. M. Eubanks, et al. (2021) in *2021 Annual Meeting of the Lunar Exploration Analysis Group* vol. 2635 of *LPI Contributions* 5036. [3] P. Lee (2018) in *49th Annual Lunar and Planetary Science Conference* Lunar and Planetary Science Conference 2982.

Artificial Thought is Required for Sustained Autonomy. Fernando Figueroa[1], [1]NASA Stennis Space Center, Autonomous Systems Laboratory, (Contact: fernando.figueroa@nasa.gov)

Introduction: The literature primarily addresses what is called "Systems Thinking." Dr. Marie Morganelli from Southern New Hampshire University states that *"Systems thinking is a holistic way to investigate factors and interactions that could contribute to a possible outcome. A mindset more than a prescribed practice, systems thinking provides an understanding of how individuals can work together in different types of teams and through that understanding, create the best possible processes to accomplish just about anything."* So, a TS is a system that is capable of "systems thinking," as it should be able to " … create [utilize] the best possible processes, and possess the [intelligence] to accomplish just about anything." To achieve this capability, human-like thinking is required. A truly autonomous system must be one that is capable of human-like thinking. Sustained autonomy requires "Thinking Autonomy" (TA) that is enabled by a "Thinking System." A foundational architecture to achieve thinking behavior should include the following systems or elements: understanding, intellect, reason, analysis, decision, communications, presentation, sensing, and will. The autonomy R&D community must address this functionality and its implementation, including software capabilities needed. The NASA Platform for Autonomous Systems (NPAS) foundationally encompasses a software architecture and core infrastructure to enable TA. NPAS is a long-term project funded by NASA's Advanced Exploration Systems (AES) and is continuing with support from the Mars Campaign Development Division (https://techport.nasa.gov/view/94884).

Thinking systems will enable a fundamental change how AI and autonomy are implemented. It will change from a "brute force" approach that results in one-time implementations that are minimally intelligent or autonomous, to a "thinking" approach where implementations evolve continuously and enable powerful intelligence and autonomy on systems of high complexity as well as on systems-of-systems.

References:

[1] Marie Morganelli (2020) *https://www.snhu.edu/about-us/newsroom/business/what-is-systems-thinking*.
[2] *https://techport.nasa.gov/view/94884*. (2023).
[3] Fernando Figueroa, Lauren Underwood, Mark Walker, and Jonathan Morris (2019) *AIAA Scitech 2019 Forum, 7-11 January 2019, San Diego, CA, USA*. [4] Fernando Figueroa, Lauren Underwood, Jonathan Morris, Mark Walker, and Rane Brown. (2022) *"Risk-Reduction Autonomy Implementation to Enable NASA Artemis Missions," IEEE Aerospace Conference 2022, March 5-12, 2022, Big Sky, Montana, USA*.

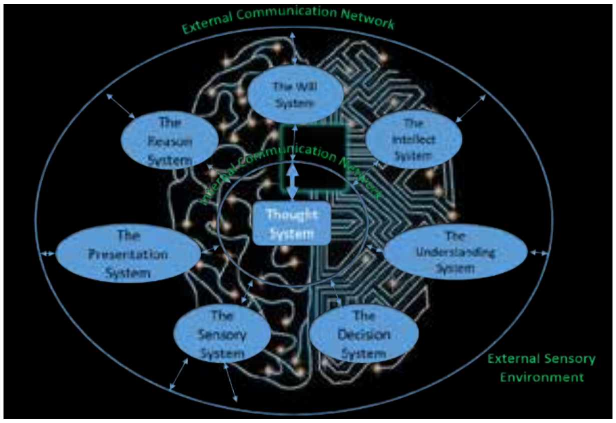


Figure 1 Architecture and Systems of a Thought System (The Autonomous System: A Foundational Synthesis of the Sciences of the Mind, by Szabolcs Michael de Gyurky, Mark A. Tarbell, John Wiley & Sons, Oct 8, 2013).

In-Space Assembly of the Gateway-Lunar Surface Development and Protection: Lunar Operations Conceptual Design I. R.H.Freeman, Space Operations & Support Technical Committee, AIAA, ronaldhoracefreeman@gmail.com

Introduction: Assembled in space like ISS, LOP-G, robots will have a 20 m linear truss structure to expand into a 10 and 50 m truss. Both a stationary robot and a mobile robot will crawl along a structure and utilize two planar dexterous manipulators to assemble individual truss pieces into a linear truss. Analogous to an ISS-EAC interaction of a haptic feedback control system, robotic assembly tasks on an orbital platform may be teleoperated from a Gateway-installed complex control station. Such concept has been demonstrated on ISS since 2011with ESA's ANALOG-1 experiment per 12 distinct METERON experiments [1]. Lunar surface development commences with a fleet of a NASA-supported robotic spacecraft touching down on the lunar soil. Masten Space's lander intends to embark on the Moon's south pole in November 2023, carrying instruments to detect water ice. Astrobotic will deliver NASA's VIPER rover on the Moon's south pole in November 2024, to explore areas in and around PSRs for over 100 days. Space weather exposes the hardware-driven mission to vulnerable risks of radiation-induced failures. A robot malfunction or failure causes unforeseen robot stoppage, resulting in economic and production losses.

ARTEMIS I mission of 2023 did not carry crew, but two identical manikin torsos wore an AstroRad vest equipped with radiation detectors, mapping internal radiation doses to areas of the body [2]. In November 2024, a crewed Orion spacecraft will perform a lunar flyby test and return to Earth. When Artemis III and its crew of four arrive in lunar orbit in 2025, a landing vehicle will take two to an awaiting robotic rover VIPER for a 7-day lunar excursion while the other two remain onboard the Gateway. The ridesharing orbital Lunar Flashlight cubesat will help choose Artemis III's landing site by finding and sampling deposits of water ice.

Space weather radiation exposes hardware, software, and humanware alike to solar particle events (SPEs) and galactic cosmic radiation (GCR). Consequences of human exposure include carcinogenesis, degenerative tissue risk, acute and late risks to the central nervous system, and acute radiation syndrome (ARS). Therefore, planetary EVAs should be planned around solar activity, but not all SPEs and GCRs are predictable, and so carcinogenesis risk mitigation is necessary for lunar visit/habitation, deep space journey/habitation, and planetary missions. NASEM reviews processes for long-term risk assessment and management for crewed missions and how to manage uncertainty of space radiation exposure risk assessments. The committee concludes that astronauts who travel on long-duration spaceflight missions are likely to be exposed to radiation levels that exceed the proposed new space radiation standard of an effective dose of 600 mSv [3].

Purpose: This paper aims to conceptualize an integrated radiation-hardened framework of lunar operations in a harsh and unfamiliar lunar climate characterized as space weather.

Methods and Results (TBD): The 2020 NASA Technology Taxonomy (Roadmap) was evaluated for areas under current R& D literature review of their respective research findings and comparatively analyzed for alignment with the framework described in the 2005 Bioastronautics Roadmap: A Risk Reduction Strategy for Human Space Exploration. The primary constraint of In-Space Assembly of the Gateway-Lunar Surface Development was space radiation for which radiation shielding helps to mitigate and radiation monitoring helps to predictably manage. Radiation shielding was described in terms of absorption per material thickness/ density as well as per multi-barrier protection design engineering of more sensitive equipment. Radiation-induced propagation of circuit failure systemic to equipment stoppage is discussed with mitigating strategies.

References:

[1] Wormnes, K., Carey, W., Krueger, T., Cencetti, L., den Exter, E., Ennis, S., ... & Grenouilleau, J. (2022). ANALOG-1 ISS–The first part of an analogue mission to guide ESA's robotic moon exploration efforts. *Open Astronomy*, *31*(1), 5-14]. [2] Gaza, R., Hussein, H., Patel, C., Meyers, T., Baldwin, M., Shelfer, T., ... & Straube, U. (2019, May). Orion EM-1 Internal Environment Characterization: The Matroshka AstroRad Radiation Experiment. In *Applied Space Environments Conference (ASEC 2019)* (No. JSC-E-DAA-TN68618). [3] Committee on Assessment of Strategies for Managing Cancer Risks Associated with Radiation Exposure During Crewed Space Missions. National Academies of Sciences, Engineering, and Medicine. 2021. Space Radiation and Astronaut Health: Managing and Communicating Cancer Risks. Washington, DC: The National Academies Press].

Effect of water content and form on the electrical properties of lunar regolith.

R.A. Gerhardt[1], W.P. Blase[2] and T.M. Eubanks[2], [1]Georgia Institute of Technology, Atlanta, GA 30332-0245, [2]Space Initiatives Inc. Princeton, WV 24740-2617 (Contact: rosario.gerhardt@mse.gatech.edu)

Introduction: Water is a basic necessity that humans need for sustenance. In addition, water can also be split into oxygen and hydrogen to provide a source of rockel fuel while generating oxygen for breathing. Recent studies have reported that there may be as much as 30% water in certain lunar locations[1], such as in the permanently shadowed regions (PSRs) on the South Pole and other locations. Working in the vacuum of space with little to no sunlight will make exploration of these regions an extremely difficult endeavor. As such, it is important to consider what experiments and simulations may be able to be done that may be able to shed light on whether a given area has the expected water content or not in order to help identify the best location for extracting those valuable resources. Our team has been working to develop a program that will allow deployment of testing equipment to different parts of the Moon to conduct experiments in-situ while the interpretation can be augmented by complementary simulations[2].

Electrical properties can be highly sensitive to the composition, size, shape and distribution in three dimensional space[3]. The composition of a given material or object can govern whether the response will be insulating, semiconducting, conducting or superconducting and as such, resistivities can range over 20 orders of magnitude (no other property can span as wide a range of values as resistivity). Such a wide range of values can only be detected by conducting measurements as a function of frequency and temperature[4].

While different frequency ranges have been explored by other investigators [5-8], most experiments tend to focus on a given frequency band which prevents detection of all possible present phenomena. It is proposed here that experiments and simulatons need to be carried out over as broad a range of frequency as possible in order to be able to track the response of the lunar regolith in detail as a function of temperature. Figure 1 displays a wide array of responses that may be observed as a function of temperature on the impedance and dielectric response as a function of frequency. These can be related to their electrical conductivity, dielectric properties or magnetic response [4].

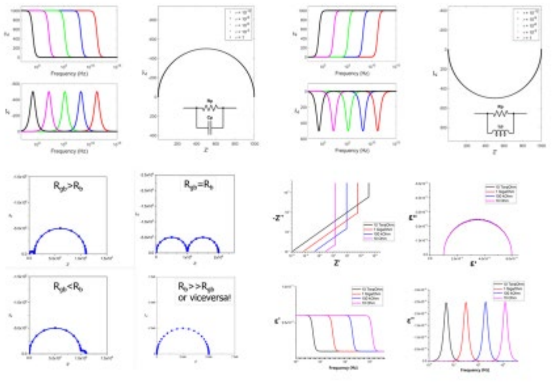


Figure 1. This image illustrates a large variety of responses that may be probed when different features dominate the frequency spectra as a function of temperature or physical arrangement of contributing phenomena. Image from Ref. 4.

In general, most of the compounds that make up lunar regolith [9] will behave as insulators or semiconductors unless they are phase separated such as the Fe nodules which have been reported in some studies of material brought by the Apollo missions [10].

When water and/or ice are combined with the lunar regolith, it is expected that liquid water will dominate the high frequency region[11] whereas the potential solid impurities and volatiles will tend to affect the lower frequencies.

References:

[1] Brown, H.M. et al., Icarus 2022, 377, 114874; [2] Gerhardt, Blasé and Eubanks, 2022 Poster 40 NESF Conference: https://sservi.nasa.gov/nesf2022/posters/detecting-water-ice-in-the-lunar-regolith-using-electrical-properties-simulation-of-the-effect-of-temperature-and-impurities; [3] Gerhardt, IEEE 2022: 10.1109/MIM.2022.9777776; [4] Gerhardt, R., Elsevier: 10.1016/B978-0-323-90800-9.00021-4 [5] Matthews, T. et al., Proc. IEEE I2MTC Conf. p. 6, Ottawa, Canada, May 16-19, 2022 [6] Artemov, V.G., Phys.Chem.Chem.Phys. 2019, 21, 8067-8072; [7] Grimm R.E., J.Phys.Chem. B 2008, 112, 15382; [8] Stroud, D., Phys. Rev. B 1975, 12, 3368; [9] Exolith Fact Sheet for LMS-1 lunar mare simulant, 2021; [10] Stillman, D.E. and Grimm, R.E.,www.lpi.usra.edu/meetings/lunargeo2010/pdf/3028.pdf; [11] Gerhardt, R.A., W. Cao, IEEE Proc. CEIDP 1996, 102-105.

Automated Reconfigurable Mission Adaptive Digital Assembly Systems (ARMADAS): Robotically Assembled Sustainable Lunar Infrastructure. C. E. Gregg[1] and K. C. Cheung[1], [1]NASA Ames Research Center, Moffett Field, CA, (Contact: christine.e.gregg@nasa.gov)

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 possible 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.

Capabilities: To date, the ARMADAS project has demonstrated autonomous assembly of large numbers of structural modules into a meters-scale structure in an earth gravity environment. 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.

Lunar Infrastructure Vision: At the LSIC spring meeting, ARMADAS will present a vision for a general-purpose lunar construction kit capable of meeting a wide variety of lunar surface infrastructure needs (Figure 1). Investing in an ecosystem of reconfigurable, discretely repairable parts and robots enables systems than can expand their capability, reconfigure to meet emergency or unforeseen needs, self-repair and reduce spare-part needs.

With a small set of parts (module types), a wide variety of infrastructure needs can be met. 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 encompass a structure to support regolith cover for a pre-integrated module to an entirely ARMADAS system-based structure. This system can be leveraged by many in-situ resource utilization (ISRU) technologies to simplify processes and augment capabilities.

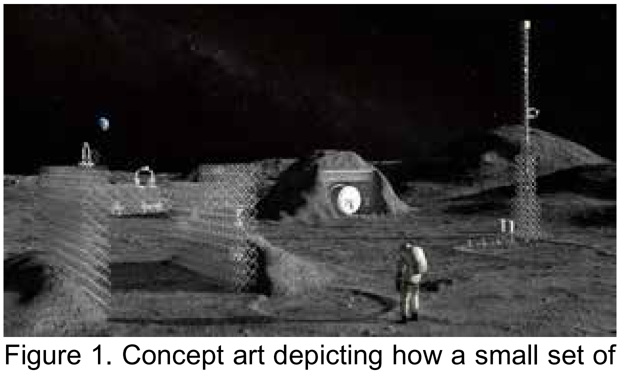


Figure 1. Concept art depicting how a small set of general ARMADAS structural module types and construction robots can meet a wide range of infrastructure needs, including towers, ISRU integration, and habitats/garages.

Ground Testing of Electrostatic Transport of Lunar Regolith Simulants with Applications to Electrostatic Sieving. P. Bachle[1], J. Smith[1], F. Rezaei[1], D. Bayless[1], W. Schonberg[1], and D. Han[1], [1]Missouri University of Science and Technology, 1870 Miner Circle, Rolla, MO 65409, (Contact: handao@mst.edu)

Introduction: Mineral benefication practice enhances and adapts the segregation tendencies of natural geologic processes to enhance the efficiency of subsequent processing and manufacturing tasks, which need appropriately sized and prepared mineral feedstock. Our LuSTR21 project directly addresses this need for lunar *in-situ* resource utilization (ISRU) through designing, building, and testing an integrated system comprised of a selection of separation subsytems for particle size classification and enrichment. At LSIC Fall Meeting 2022 we reported our progress on developing a modeling capability to simulate electrostatic transport of lunar regolith particles with applications to electrostatic sieving. Particularly, concept designs proposed by Kawamoto and Adachi [1] using traveling-wave configuration of electrodes are to be modeled and simulated. The electric field is solved by an immersed-finite-element (IFE) Poisson solver [2] while the motion of charged particle grains are tracked by a kinetic approach [3]. A typical electric potential solution is given in Fig.1 below, while Fig. 2 shows a screen shot of grain trajectories at a certain time step.

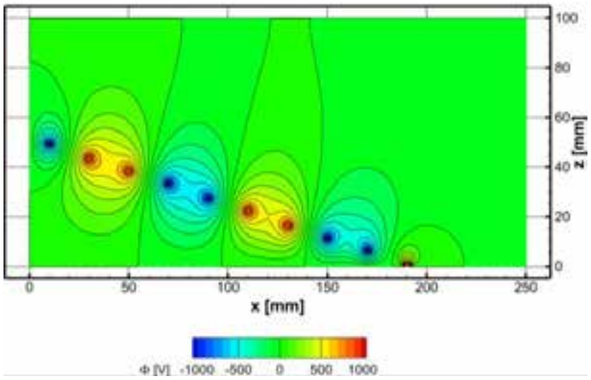


Fig. 1. Potential contours of one phase of a four-phase electrostatic traveling wave.

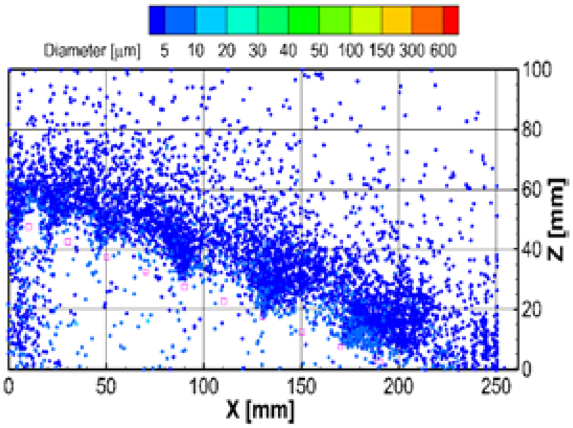


Fig. 2. Trajectories of grains at a selected time step. Grains are colored by size. Electrodes are shown as purple boxes.

For this upcoming LSIC Spring Meeting 2023 we will report our preliminary results on ground testing of the prototype electrostatic sieve hardware, as shown in Fig. 3. Particularly, efficiency of size classification of the electrostatic sieve concept will be compared with the modeling results.

Fig. 3. The prototype of the electrostatic sieve as configured in a glove box ready to undergo testing of size separation of lunar simulants.

References: [1] Kawamoto and Adachi. (2014) *AIAA 2014-0341*. [2] Kafafy. et al. (2005) *Int. J. Num. Methods. Eng., 64, 940-972*. [3] Zhao. et al. (2022) *J. Aerospace Eng.*, 35(6): 04022095.

Transparent composite film for passive cooling of solar panels. M. Harbinson[1], M. Pudlo[1], S. Liu[1], Y. Liu[1], C. Sui[2], Y. Zhu[1], P. Hsu[2], and J.E. Ryu[1], [1]Department of Mechanical and Aerospace Engineering, North Carolina State University, 1840 Entrepreneur Dr., Raleigh, NC 27606, Partners Way, Raleigh, NC 27606, [2]Pritzker School of Molecular Engineering, University of Chicago, 5460 S Ellis Ave. Chicago, IL, 60637 (Contact: jryu@ncsu.edu)

This study investigates the use of roll coated composite films for use in the passive radiative cooling of photovoltaics. Solar panels show decreased efficiency at higher temperatures [1]. Additionally, thermal regulation becomes of increasing importance in spacecraft and lunar environments where temperatures exceeding 120°C and the lack of convective heat transfer make the cooling of spacecraft increasingly difficult [2]. The International Space Station currently relies on active thermal control systems in order to reject waste heat to make itself habitable using valuable energy, as such, passive cooling technologies such as our proposed film are being further explored for space uses. The experimental composite coating uses nano-particles embedded in a polymer matrix. The purpose of these nano-particles is to increase the infrared (IR) emission of the underlying surface to aid in lowering the surface temperature of the underlying solar cell. Additionally, any surface texture of the films will increase the total emission from the surface [1].

In manufacturing these films, the ribbing instability seen when a fluid passes between two rollers was exploited. The two rollers create a pressure gradient and apply shear stress which causes these defects to occur [3,4]. With certain roller parameters, such as distance and speed, these defects can be forced to create spikes. A custom-built roll coating machine was used to fabricate samples. This machine consisted of two stainless steel rollers 300 mm in length and 50 mm in diameter. The gap between these rollers can be adjusted from 0 to 10 mm with an accuracy of 10 µm.

Our proof-of-concept tests utilized spherical SiO_2 nano-particles 20-30 nm in diameter dispersed in a polydimethylsiloxane (PDMS) matrix. The purpose of the particles is to both modify the viscosity of the PDMS as well as increase the IR emittance. Additionally, SiO_2 is visibly transparent allowing for these films to be used for solar cell applications [5]. PDMS was chosen due to its visible transparency and high IR emission [6].

The composite films were designed to satisfy two optical criteria: Visible transparency and high IR emittance. The films were also designed to have rough surface textures which were induced by the roll coating process. Eight films were created using 4, 6, 8, and 10 volume percent SiO_2, with a flat and rough sample being made for each volume percent. The rough samples were created by utilizing a roller distance of 0.1 mm and a roller speed of 100 rpm.

These films underwent testing to characterize their surface and optical characteristics. Through water contact angle testing, it was found that the rough higher volume percentage samples had larger water contact angles near 130°, thus around 20° higher than their flat counterparts. Hydrophobic surfaces have low surface energies making adherence to dust more difficult and could be applied in lunar or Martian applications [7]. Utilizing laser confocal microscopy, it was found that both the 8 and 10 percent samples had very high peak density with an average spacing of 400-500 µm, which resulted in the corresponding water contact angles and improves both self-cleaning and emissive properties of the films.

Both UV-Vis and FTIR Spectroscopy were performed to characterize the optical properties of the fabricated films. The films show increased absorptance in the ultraviolet and near infrared wavelengths whilst having three notable dips at 9.1, 9.8, and 12 µm which correspond aptly to the atmospheric window. These films displayed low absorptance between 400-11000 nm which allows visible light to be transmitted to the solar cell beneath. Additionally, it was seen that the rough samples and high-volume percent samples experienced a higher absorptance than the flat samples and low volume percent samples. Outdoor solar panel passive cooling tests performed utilizing the 8% and 10% rough samples displayed a cooling of 3.5°C versus a control sample.

[1] B. Zhao, et. al. (2020) *Applied Energy,* 262, 114548 [2] R. Almehisni, and F. Naimat (2018) *ASET International Conferences*, 1-6 [3] E. Szczurek, et al. (2009) *J. Mater. Process. Technol. 209*, 3187. [4] A. J. Babchin, et al. (1981) *Adv. Colloid Interface Sci. 14*, 251. [5] H. Bao, et. al. (2017) *Solar Energy Materials and Solar Cells, Volume 168,* 78-84 [6] V. Prajzler, et. al. (2017) *Mater Sci: Mater Electron 28*, 7951–7961 [7] Y. Lin, et. al. (2011) *AIAA Atmospheric Space Environments Conference*

Planning and Initial Performance of a Cislunar Position, Navigation, Timing, and Communications Service. M. Hartigan, D. Smith, and G. Lightsey, Space Systems Design Lab, Georgia Institute of Technology, Atlanta, Georgia USA, 30332. (Contact: hartigan@gatech.edu)

Introduction: In recent years, organizations such as NASA and the ESA have shown interest in establishing a position, navigation, timing, and communications (PNT-C) service in cislunar space [1,2]. In anticipation of the design and fielding of a cislunar PNT-C system, researchers at the Georgia Institute of Technology have been developing a plan for a comprehensive and scalable PNT-C architecture around the moon. This study proposes a phased approach to delivering PNT-C satellites to first serve areas of scientific interest – such as the lunar south pole – followed by eventual coverage of the entire lunar surface and a service volume in cislunar space.

Architecture: The proposed PNT-C system is implemented in three distinct phases of operation, and each is characterized by system assets and performance accumulated at that time. Phase I consists of a small number of PNT-C satellites placed in selected orbits to maximize coverage and availability to regions of interest on the lunar surface. Phase II includes additional PNT-C satellites, launched in blocks, in complementary lunar orbits in order to expand the zone of coverage while also providing higher accuracy navigation solutions. In addition, Phase II adopts ground stations and beacons deployed during surface missions to create a network of service assets. Finally, Phase III will see the completion of the PNT-C system with a constellation of satellites providing global coverage of the lunar surface and orbit volume.

The technology utilized by the system will also evolve as the phases progress. Select blocks of PNT-C satellites will employ both radio frequency and optical signals, which will support a necessary increase in bandwidth while the user base increases in number. These progressive upgrades will diversify the system in order to effectively fulfil the varying requirements of users based on their navigational and communication needs. Considerations have been made to align this proposal with current international policies [3,4] and strategic objectives such as LunaNet [1].

Performance: Analysis tools were developed to evaluate the navigation performance of potential architectures. The study includes a thorough characterization of error sources, dilution of precision for users, and constellation coverage. Software-in-the-loop simulations were used to model errors due to clock drift, satellite orbit determination uncertainty, receiver noise, multipath, and lunar regolith in order to determine an estimate of the end-user navigation error for a given satellite constellation. Studies are being conducted to recommend different filtering methods based on use case and phase of development – e.g., batch versus sequential estimation algorithms.

A case study of navigation system performance for surface users on the lunar south pole is presented. Different low-infrastructure Phase I constellations are examined on the basis of cost of deployment, coverage, availability, and navigation performance for a lunar ground station and surface rover, respectively. These constellations are drawn from both literature and original work, with a focus on minimum viable infrastructure to provide useful navigation solutions. Results from utilizing different navigation algorithms and filtering methods for each case are quantified. Comparisons between different early-stage constellation designs are made in regards to orbit stability and station keeping costs.

Results: A method for obtaining a standard characterization of performance is developed with results showcasing achievable performance for a Phase I cislunar PNT-C system. This tool will also serve as the baseline for the analysis of future phases of development with additional satellites in a variety of other orbits. Future analysis will include navigation performance for use cases across the entire lunar surface – beyond those limited to the lunar south pole.

References: [1] Israel D. et al. (2020) *2020 IEEE Aerospace Conf.,* 1-14. [2] Giordano P. et al. (2022) *2022 International Technical Meeting of The Institute of Navigation,* 632-642. [3] NASA (2020) *The Artemis Accords*. [4] Space Frequency Coordination Group (2022) REC SFCG 32-2R4.

Advancing Autonomous Excavation and Construction for Sustained Lunar Exploration.

S. Hasnain[1,2], A. Chatterjee[1,2], J. Abraham[1,2], C. Knez[1,2], M. Nord[1,2], M. Hilburger[3], [1]Johns Hopkins University Applied Physics Laboratory, [2]Lunar Surface Innovation Consortium, [3]NASA Space Technology Mission Directorate. (Contact: Sarah.Hasnain@jhuapl.edu)

Introduction: “To change the space exploration paradigm from **‘there and back again’** to **‘there to stay,’** we’re going to need **robust**, **resilient**, and **broadly capable systems** that can use the local resources of the Moon and other planetary bodies” – Jason Ballard, CEO of ICON [1].

Image Credits: ICON / BIG-Bjarke Ingels Group [2]

From launch and landing pads, to roads and berms, habitats, and more, autonomous construction capabilities are imperative to enabling sustained operations on the Moon, Mars, and beyond.

State-of-the-Art and the Future of Autonomous Construction: Technologies enabling autonomous lunar construction capabilities are being developed in real-time – from pre-integrated solutions to be deployed upon arrival to the lunar surface, to those which are pre-fabricated, requiring assembly, as well as those which are in-situ resource-derived [3]. Considerations include infrastructure such as power and communications; environmental factors including radiation and dust mitigation; model transparency among stakeholders; computing resources for model refinement; frameworks defining the meaning of “autonomy”, articulating autonomy vs. AI, and characterizing autonomous technology capabilities [4].

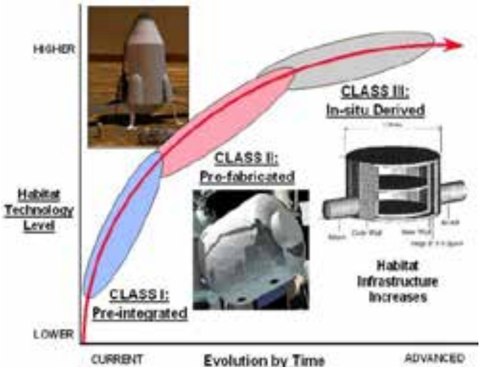


Image Credits: Kennedy, K. J. [3]

LSIC and Community Efforts: The Lunar Surface Innovation Consortium (LSIC) spans industry, academia, and government – empowering development of transformative capabilities in key technology areas, including Excavation & Construction – towards the broader goal of a sustained presence on the lunar surface.

LSIC Excavation & Construction efforts include meetings focused on master planning, environmental considerations, and featured presentations by stakeholders across the community landscape, including translational innovation via technology developers who specialize in Earth-based construction [4]. There are four subgroups which engage in deeper discourse regarding related topics: Autonomy & Site Planning; Additive Manufacturing & Raw Materials; Site Prep, Horizontal & Vertical Construction; Outfitting & Maintenance.

Further, in Summer 2023, the LSIC Excavation & Construction Focus Group plans to partner with the LSIC Extreme Access Focus Group to host a dedicated workshop centered on autonomy.

Conclusion: Autonomous construction capabilities are critical to building an enduring lunar presence. This presentation will discuss both state-of-the-art and the future of autonomous lunar construction as well as initiatives catalyzed by the LSIC Excavation & Construction Focus Group.

References:

[1] Alamalhodaei, A. (2022). *Max Q: Building on the Moon and Mars*. TechCrunch. https://techcrunch.com/2022/12/05/max-q-building-on-the-moon-and-mars/. [2] Frazier, S. (2022). *NASA, ICON Advance Lunar Construction Technology for Moon Missions*. NASA. https://www.nasa.gov/press-release/nasa-icon-advance-lunar-construction-technology-for-moon-missions. [3] Kennedy, K. J. (2002). The Vernacular of Space Architecture. *AIAA Space Architecture Symposium*. https://doi.org/10.2514/6.2002-6102. [4] The Johns Hopkins University Applied Physics Laboratory (n.d.). *Excavation and Construction*. Lunar Surface Innovation Consortium. https://lsic.jhuapl.edu/Our-Work/Focus-Areas/index.php?fg=Excavation-and-Construction.

Bad Moon Rising: Artemis Discord, A Futures Thinking Innovation Initiative.

A. Haufler[1], B. Rupert[1], L. Barbano[1], S. Whitley[1], S. Withee[1], S. Brothers[2], J. Asher[2], R. Fuller[1], W. Fuhrman[1]. [1]Johns Hopkins University Applied Physics Laboratory, 11100 Johns Hopkins Road, Laurel, MD 20723, [2]The Aerospace Corporation, 2310 E. El Segundo Blvd., El Segundo, CA 90245 (Contact: Amy.Haufler@jhuapl.edu)

Introduction: Globally increasing interest in the lunar surface and emerging capabilities that enable activities there may lead to overlapping spheres of activity and ultimately competition on the Moon. Artemis Discord focused on scenarios that addressed multiple elements of the competition-to-conflict spectrum and identified pathways toward enabling policies and technologies needed to achieve a sustained, successful U.S. lunar enterprise.

Approach: This project conducted analysis of U.S. cislunar and lunar stakeholders through semi-structured interviews and a tabletop exercise. We will present results of the analysis, including perspectives of stakeholders within the civil, industry, and national security communities; commonalities and gaps across the communities; and opportunities for future stakeholder involvement.

Stakeholder Engagement: This effort was centered around an interview-based analysis of the lunar and cislunar communities. Stakeholders from across the United States civil, industry, national security, and policy communities (n=29) with interest in cislunar space and lunar surface exploration and economic development participated in semi-structured interviews. Questions focused on the context of a competitive, multi-national cislunar and lunar surface presence on the 20-year time horizon. Interview questions were designed to elicit stakeholders' concerns regarding plausible threats and competition-to-conflict activities in the near-, mid-, and long-terms and to identify mission responsibilities, expectation, and operational flows between the communities in the event that future should be realized.The transcripts and notes from these were hierarchically coded and thematically analyzed.

Table Top Exercise: The second phase of the project conducted a lunar-to-cislunar tabletop exercise (TTX) in which plausible cislunar and lunar surface competition scenarios and unified responses by United States stakeholders in *circa* 2040 was explored. The exercise presented three interconnected scenarios developed from common themes in stakeholder interviews and an assessment of international lunar surface and cislunar assets possibly fielded by 2040. The scenarios address several areas of concern (as revealed in stakeholder engagement) within the technical and policy communities, including situational awareness of objects in lunar orbit, cislunar space, and on the lunar surface; international disputes regarding freedom of action on the lunar surface, including surface rights; and the lack of attributable intelligence in a contested lunar surface environment. Two blue teams consisting of members of the civil, industry, and national security communities responded to the scenarios in parallel. A red team - consisting of Applied Physics Lab experts in adversary behaviors and space technologies - played the role of the People's Republic of China, the primary operator of the International Lunar Research Station.

Results: Results of and observations from the TTX, recommendations for both technology and policy stakeholders and next steps for this futures thinking project will be presented.

.

Material Release request number OTR202300396, entitled "Abstract - A Moon-wide Concept for Cargo Transport Using neither Water nor Fuel" has received final OTR approval for Public Release by the Office of Technical Relations – February 8, 2023.

Lunar Surface Innovation Consortium Spring Meeting

Title of Abstract. A moon-wide concept for cargo transport using neither water nor fuel

Thomas Heinsheimer[1], [1]The Aerospace Corporation, 2350 El Segondo Blvd, El Segondo CA 90045. (Thomas.heinsheimer@aero.org 310 984-9230

Introduction: This paper proposes that low-mass intra-lunar transportation and moon-to-Earth transfers could be accomplished without water or rocket fuel by applying sustainable electrical power to centrifugal machines. Such a device has been successfully prototyped and operated by SpinLaunch,Inc for future Earth to Orbit applications.

Concept: The centrifugal approach does not constrain the location of any robotic lunar outpost to a source of water; it can operate autonomously at any location on the front or back of the moon. Networks of such outposts could be linked by centrifugal machines, to transfer cargo from anywhere on the moon to anywhere else, within a day.

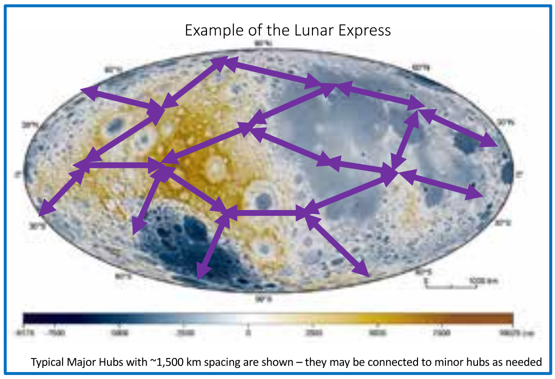
Using solar or nuclear power, we drive a rotary mechanism to accelerate small (~25 kg) projectiles to the needed velocity to move them from place to place on the moon, or to bring cargo from the moon to Earth.

CONOPS: A solar power supply (with 25 percent efficiency) is illuminated for half of the 28-day lunar cycle anywhere on the moon. For operations during the 14 Earth-days lunar night, we either use a nuclear power source instead of solar cells, or include storage batteries. The typical weight for electric vehicle automobile lithium-ion storage batteries is approximately 30 kg/kw-hr. Each launch of a 25 kg payload at a 1,500 km range requires 750 kg of batteries. Improving the conversion efficiency from 25 percent would reduce the battery weight accordingly.

To allow continuous operations, not dependent on the sunlight cycle, we can use a nuclear power system such as a 40 kw source being developed by NASA—this would eliminate the need for large batteries for lunar night operations.

LunEx Network: We consider incremental placement of stations to form the "*Lunar Express Cargo Transportation Network*"—"*LunEx*." Each network node would contain a kinetic launcher, its power supply, a landing mechanism, and the robotics to collect incoming cargo and rapidly pass it on the launcher for onward transfer. The maximum interstation distance would be about 2,000 km to not exceed lunar escape velocity of about 2.5 km/sec.

In an example we postulate major stations at 1,500 km distance and perhaps minor stations, as needed, for closer range support. For 1,500 km distance, the flight time is about 0.5 hours—so if the in-station transfer took another half hour, the cadence of launches could be about an hour (power dependent). As the lunar circumference is approximately 11,000 km, the maximum separation between a station sending cargo and one receiving it would be about 5,500 km, requiring some 4 hops of 1,500 km each. Such a network could therefore deliver cargo from any station to any distant station in less than 4 hours.


Example of the Lunar Express

Typical Major Hubs with ~1,500 km spacing are shown – they may be connected to minor hubs as needed

Courtesy of NASA (with Aerospace Overlay)

Figure 1 – Artists Concept of the LunEX Network

Moon to Earth: We modeled notional flights to understand the geometric and time-related possibilities and constraints of moon-to-Earth transfers via centrifugal launch. For an arbitrary departure date, a transfer from the near side of the moon will require approximately 2500–2700 m/sec and about 3.7–5.7 days to deliver cargo to an arbitrary location on Earth. For different departure epochs and locations, and Earth landing locations, the departure vector (DV) numbers are all pretty much the same.

References:

[1] Heinsheiner, et al. (2023) *Overcoming the "Tyranny of Water" Using Electrical Power to Replace Rocket Fuel in Moon-wide Operations* Space Power Workshop, Redondo Beach Ca, April 2023.

PNEUMO PLANET Inflatable Moon Habitat:

Thomas Herzig: Lead Designer at pneumocell, www.pneumocell.com,
Weyringergasse 29/17, 1040 Vienna, Austria, Phone: +43 699 11101220 , info@pneumocell.com

Gabor Bihari: Physicist, Department of Experimental Physics, University of Debrecen, 18/A Bem sq. Debrecen, H-4032 Hungary

Norbert Kömle: Astrophysicist, at the Space Research Institute (IWF), Austrian Academy of Sciences, Schmiedlstrasse 6, A-8042 Graz, Austria

Introduction:
Funded by the European Space Agency, we designed and developed a concept for a habitat suitable for a permanent presence on the moon,that was finished in summer 2022.
It shall be located in the close vicinity of one of the lunar poles and demonstrates the feasibility of the suggested design in view of the available resources. The habitat shall operate self-sufficiently in the long term by pro-ducing and recycling its own oxygen and food inside large greenhouses and almost exclusively by using solar irradiation power.
The concept features a combination of:

1. Prefabricated ultra-light inflatable structures.
2. Covering the inflated structure with a 4 -5 meters thick layer of local loose regolith for efficient protection from extreme temperature, meteorites and cosmic radiation.
3. The use of mirrors that move towards the sun and bring visible sunlight into the greenhouses.

The habitat structure consists of room modules that can be connected to extend the habitat. The main modules are toroidal greenhouses with a minor diameter of about 5 m and a major diameter of 22 m. These greenhouses are connected among each other by a tunnel system and additional modules for living and working areas are attached to their outer side. The habitat can start with one greenhouse unit and grow by adding more greenhouse units. As a baseline, we suggest a station consisting of 16 greenhouse units that are placed in a double linear arrangement, in order to minimize mutual shadow casting among the mirror towers, when the Sun moves along the lunar horizon. Moreover, a redundancy of the corridors keeps the parts connected even if some parts are destroyed in an accident. The regolith layer covering the inflatable modules acts as a very effective thermal isolation between the interior of the greenhouses and the surrounding environment, as has been verified by a numerical modeling. The upper mirrors reflect the nearly horizontally arriving sunlight into an artificial crater at the geometric centre of the torus, from where it is directed into the greenhouses via another conical mirror into the greenhouse.
The needs for materials and consumables were estimated and ways for a suitable recycling system were pro-posed. Oxygen is produced by the plants in the greenhouses, which in turn use the CO2 exhaled by the crew for their photosynthesis. Additionally excrements plus non-edible parts from plants are composted into fertile soil again. Excess CO2 is stored in a cryogenic container. Photovoltaic panels fixed to the rotating mirrors produce the necessary electro-power.

Compared to other recently published studies, our PneumoPlanet design features by far the lowest payload weight, the most effective protection from cosmic particle radiation, and the lowest energy requirement for the construction process and in operation. Additionally, it is the only concept of all published until now, that provides a complete ecological cycle for self-sufficient production of food and oxygen.

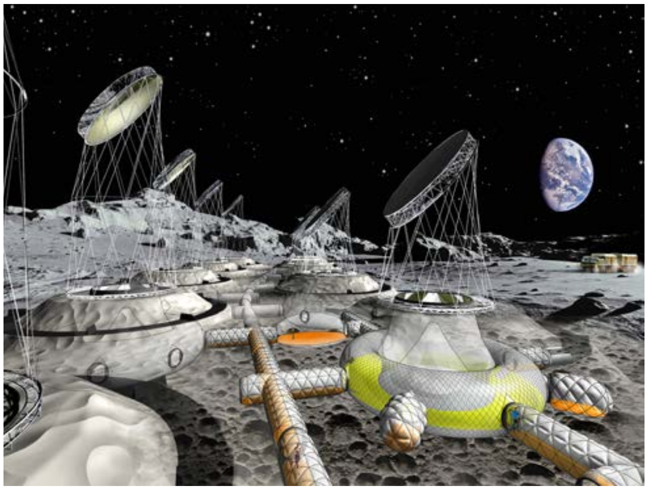
References:
[1] *https://youtu.be/1rOLgS_StSc*

[2] *https://moonhabitat.space*

[3] *https://pneumocell.com/projects/pneumo-planet-moon-habitat/*

[4] *https://www.esa.int/ESA_Multimedia/Images/2020/09/Inflatable_Moon_base*

[5] Herzig T. , Koemle N.I., Macher W., Bihari G. , Glaeser P.: Site selection, thermodynamics, environment and life support analysis for the PneumoPlanet inflatable lunar habitat concept. Planet. Space Sci. 224, 105595 (2022), *https://doi.org/10.1016/j.pss.2022.105595*



The Science of Autonomy. W.E. Hollier, Director, EnGen Institute, 8 The Green, Ste 300, Dover DE 19901. (Contact: william.hollier@engen.institute)

Introduction: Autonomy in space means independence from resupply from Earth, which requires having the capability to harvest all materials and manufacture and repair all machines in the lunar colony, including any supporting infrastructure.

This in turn requires that production capability of some subset of these machines includes the capability to produce all the machines of the colony, which is a form of closure via self-reference, specifically product-process co-design closure (PPCC). This self-referential design requirement is beyond current engineering design methodologies, but within the standard tools and methods of computer science as meta-level constraints.

Solution: Consequently, just as CAD and EDA design software is based in computer science but addresses engineering design, enhanced design software capable for processing self-referential design constraints can augment engineering design methods to address self-reference.

These meta-level constraints still allow any selection of materials, processes and designs that meet the PPCC requirement. Lunar colony developers would make these selections, just as they currently do, but include the PPCC constraint in their requirements.

Implementation: These specifically selected self-referential constraints are then just additional constraints included in the MOSA catalogue of required standards applicable to the lunar colony and its infrastructure. So, an earlier form of the design standards implementing the selected variant of self-referential design capability could be available as a knowledgebase.

When fully developed the design software enhancement would be a post-processor of CAD and EDA designs and/or a design advisor incorporated into CAD and EDA software.

NASA Study: The application of self-referential design concepts to lunar manufacturing and settlement was first investigated in NASA's Advanced Automation for Space Missions [1] study.

The foundational science inspiring NASA's landmark AASM study is John von Neumman's studies of self-replicating automata [2].

This study, considered some small high technology components would be both too difficult to manufacture on the Moon and would add little to the upmass requirements to sustain the colony. These were termed 'Vitamin' parts and a measure of autonmy called the Tukey Ratio defined.

Tukey Ratio: The 'mass of materials supplied from Earth as a proportion of the total mass of finished materials consumed by the lunar colony' effectively measures autonomy in terms of saved upmass or launches. If only 'Vitamin' parts (e.g. chips, bearings) are delivered the Tukey Ratio is a small number and zero for total autonomy.

Recycling: The NASA study was based on what is now called a 'linear' economy and did not consider recycling and a 'circular' economy. So materials were only sourced from Earth or ISRU.

When refined materials are required recycling is often far more energetically efficient than either Earth supply or the mining and smelting of ISRU.

For far from Earth, long duration voyaging, onboard repair and regeneration from recycled materials is highly desirable.

Material Process Cycles: For regeneration via recycling to be feasible and comprehensive, for every material in use, a cycle of material transformations including refining/purification, shape forming, assembly and disassembly are required. Adopting such materials processing closed-cycles (MPCC) as best practice design will enable and enhance autonomy, survivability and reduce cost by lowering the Tukey Ratio.

Automation: The Astronaut workload is a limiting factor, so automation and teleoperation are advantageous.

Automating the MPCC of each material leads to high-levels of energy efficient recycling and a highly automated production capability, that is a platform enabling PPCC and thereby high levels of autonomy and survivability.

Further Development Potential: NASA's AASM study considered applying self-referential design to automation resulting in self-assembling robots, fully automated lunar manufacturing and ultimately a self-replicating lunar settlement able to multiply its own manufacturing capacity.

References: [1] Freitas R. A. and Gilbreath W. (1982) *Advanced Automation for Space Missions,* NASA Conf. Pub, 2255. [2] Von Neumann J. (1966) *Theory of Self-reproducing Automata*, Burks A.W. (ed.), University of Illinois Press.

Surving the Unexpected – Designing and Implemnting Safety Controls. R. Jain[1], [1]Purdue University, 18 S 4th Street, Lafayette, IN, 47901 (jain356@purdue.edu)

Abstract: Space habitats will face unpredictable environments while being tightly coupled and resource constrained. Therefore, it's unlikely that the habitats can be designed with many redundant safety controls, or with safety controls that address every possible hazard. Our proposed approach helps identify controls that are likely to be effective against both foreseen and unforeseen hazards. We model systems from a state-based perspective where the system is in one of four distinct types of states at a given time: nominal, hazardous, safe, or accident. Safety controls prevent the system from entering or remaining in a hazardous or accident state or transition the system to a temporary safe state or to a nominal state.

We have established an extensive database of disruptions that could affect a lunar habitat, associated safety controls, and a control effectiveness measure which evaluates the effectiveness of a safety control in addressing the hazard for which it is designed.

To address the challenge of unforeseen hazards, we are developing ways to design and select sets of safety controls that effectively address hazards for which they were not originally designed. Our hypothesis is that such high "resilience power" safety controls will result in habitats with high resilience. For an initial estimate of resilience power, we implement each safety control for multiple disruptions and record its control effectiveness for each disruption. We are studying concepts from literature on flexibility and agility to refine our measure for resilience power, and to identify ways to design safety controls with high resilience power.

Habitats with high resilience power and control effectiveness safety controls should be resilient to both foreseen and unforeseen hazards if our metrics are well-designed. We are testing this hypothesis by running simulations on RETHi's three test and simulation platforms: the MCVT, CDCM, and CPT.

Full-Scale Physical Lunar South Pole Surface Lighting Simulation

E. K. Jaynes[1] and T. C. Bryan[2], [1,2]NASA's Marshall Space Flight Center, Huntsville Alabama. (Contact: emma.k.jaynes@nasa.gov)

Introduction: The lunar south pole is a desirable landing location for the Artemis Program due to the presence of ice and other resources. But polar lighting conditions present many potential risks. Viewed from the pole, the Sun moves laterally across the horizon, and never crosses more than 1.5 degrees above or below it [1]. The lowest sunlight angle experienced by Apollo astronauts during an EVA was 7.49 degrees above the horizon [2]. The permanently low sun angle at the poles creates harsh sunlight and shadows, more extreme than those experienced by previous astronauts on the lunar surface.

In June 2022, the NASA Engineering and Safety Council (NESC) held a Lunar Surface Lighting Workshop with subject matter experts across NASA in an effort to derive architecture-level requirements for Artemis lighting systems. Prior to the workshop, the NESC identified that Earth has no physical analogs for a lighting environment with three key lunar characteristics: (1) the sky is black, (2) the sun's rays are parallel with the ground, and (3) these conditions can persist for two weeks uninterrupted.

Objectives: In support of the NESC workshop, the engineering team at the Flat Floor Robotics Laboratory (FFRL) at NASA's Marshall Space Flight Center (MSFC) designed, assembled, and demonstrated a full-scale physical simulation of the illumination environment present at the lunar south pole. The FFRL Lunar Lighting Simulation (FLLS) satisfies each of the NESC's characteristics while being large enough to support human participants.

Methods and Results: The interior of the FFRL is lined with black curtains, and the walls were designed to eliminate outside light sources from the rest of the building, to simulate the background of space. The FFRL is also equipped with a dynamic solar simulator consisting of six 6 kW and one 12 kW ARRI movie lights. These lights are normally mounted on a two-axis simulator that translates along overhead rails and yaws to allow pointing at different targets in the lab. To achieve the low light angle present at the lunar pole, these lights were brought down from the simulator and aligned with the edge of the simulated lunar surface area. Because the FFRL is an interior, climate-controlled facility, testing conditions can be maintained for extended periods of time. The limiting factor is the lifetime of the Hydrargyrum Medium-Arc Iodide (HMI) light bulbs. Each bulb can burn for hundreds of hours and can be replaced in minutes.

Future capabilities of the FLLS includes the addition of partial gravity offloading. The Dynamic Overhead Target Simulator (DOTS) is an eight-axis overhead robotic arm located in the FFRL. This arm will be used with a linear air spring to offload the weight of a test subject and simulate lunar gravity. Work by Alvin Harvey at MIT provides a basis for harness designs best for partial gravity offloading [3], which will allow participants to engage for longer periods of time and experience less strain from the harness. The size of the simulation area can accommodate large mock-ups, such as landers and rovers, for testing with more complex lunar architexture. Fidelity can be increased by incorporating analog space suits to mimic the restrictive movements required to perform lunar EVAs.

Conclusion: The current and future capabilities of the FLLS make it an invaluable physical analog for lunar lighting conditions. The size of the set-up allows an active test subject to physically move through the space and experience the intensity of light and shadow produced by the solar simulator, which is an advantage over computer simulations. This will allow for the continued characterization of the lunar illumination environment, and the development of mitigations to protect both human explorers and hardware.

References: [1] Wright, E. (2021) *NASA's Scientific Visualization Studio,* Earth and Sun from the Moon's South Pole. [2] Lawrence, B. W. (2005) *Apollo Lunar Surface Journal*, Sun Angles [3] Harvey, A. D. (2018) *MIT*, Partial Gait Simulators, Harness Design, and an Examination of Gait Transitions in Partial Gravity.

Figure 1: Overhead view of the FLLS in use

Investigation on the Use of Acoustic Waves, and Potential Coupling Material Efficiency, as a Non-Destructive Evaluation (NDE) Method Applied to Potential In-Situ Resource Utilized (ISRU) Building Materials Exposed to Vacuum. C. Dreyer[1] and I. Jehn, P.E.[2], [1&2]Colorado School of Mines, Center for Space Resources, 1310 Maple St., GRL 234, Golden, CO 80401. (Contact: cdreyer@mines.edu)

Abstract: NDE methods utilizing acoustic waves have been used in terrestrial concrete construction for many years to determine concrete quality and material properties. This research investigated the use of acoustic inspection techniques applied to potential lunar surface construction materials. Two acoustic methods were investigated. The Ultrasonic Pulse Velocity method outlined in ASTM C597 (Standard Test Method for Pulse Velocity Through Concrete), and the Resonant Acoustic Method outlined in ASTM C215 (Standard Test Method for Fundamental Transverse, Longitudinal, and Torsional Resonant Frequencies of Concrete Specimens).

The goal of this research was to determine the feasibility of acoustic investigation methods to characterize ISRU lunar building materials without the need for special test samples to be made. This was done in an effort to develop a NDE method to investigate a printed pad surface located on the Moon, that can determine material properties without the need for additional test equipment (like a compressive or modulus of rupture test frame).

Both ASTM methods were applied to terrestrial construction products and simulated ISRU building materials. Tests were conducted in both normal atmospheric conditions, and in a Technology Readiness Level (TRL) 5 environment, with the acoustic transducers operating in a vacuum chamber on samples bearing on simulated lunar regolith (CSM-LHT). These efforts were done to evaluate the effects on wave speed, transmission, propagation, and the coupling material efficiency. The results indicate that these techniques have good potential use in the lunar environment for building material characterization.

Figure 1: TRL 5 test set-up in vacuum chamber.

Figure 2 provides example results from this investigation. It indicates the resulting waveform from ultrasonic pulse transducers applied to a simulated sintered regolith tile using silicon rubber as the coupling material. The time required for the waves to pass through the material, otherwise known as wave speed, is the same when the material is located within normal atmospheric conditions and in a vacuum environment.

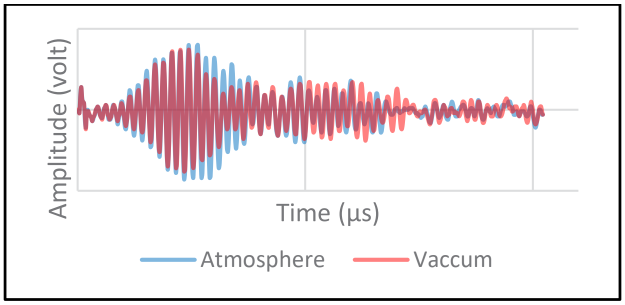


Figure 2: Ultrasonic pulse velocity waveform of basalt sintered tile coupled with silicon rubber.

Additionally, an evaluation was conducted on coupling material efficiency for the Ultrasonic Pulse Velocity method. Multiple coupling materials were tested that have low off gassing potential and can be used in a vacuum environment. Effects on wave speed and transmission efficiency were determined for use in future instrument development.

Acknowledgements: This work was partially supported by Moon-to-Mars Planetary Autonomous Construction Technology (MMPACT), contact number 80MSFC22CA007. The authors also thank Olsen Engineering, Inc. for their advice and acoustic equipment loan.

References: [1] ASTM Standard C215. (2020) *ASTM International. 04.02*, C09.64. 91.100.30. [2] ASTM Standard C597. (2016) *ASTM International. 04.02.* C09.64. 91.100.30. [3] Al-Khafaji S. and Purnell P. (2016) *Journal of Civil and Environmental Engineering. Vol 10,* No:2. [4] Bentama, J. et al. (2007) *Desalination. 206(1–3),* 1–8. [5] Chang, L. et al. (2000) *Materials Characterization. 45(3*), 221–226. [6] Garnier, V. et al. (2013) *Construction and Building Materials. 43,* 598–613. [7] Lafhaj, Z. et al. (2006) *Cement and Concrete Research. 36(4),* 625–633. [8] Liao, W. et al. (2022) *Earth and Space 2022.* [9] Özkan, İ. and Yayla, Z. (2016) *Ultrasonics. 66,* 4–10. [10] Romagnoli, M. et al. (2007) *Journal of the European Ceramic Society. 27(2–3),* 1631–1636.

Lunar Vertical Takeoff and Vertical Landing (VTVL) Pad Design Methodology, and Hypothetical Pad Analysis. I. Jehn, P.E.[1], C. Dreyer[1], and T. Nguyen[2], [1]Colorado School of Mines, 1310 Maple St., GRL 234, Golden, CO 80401, [2]ICON 220 E St Elmo Rd, Austin, TX 78745. (Contact: ijehn@mines.edu)

Abstract: Before beginning any structural or civil engineering design project, it is typical for the Designer or Record to draft a Basis of Design (BOD) document to organize all anticipated design parameters, variables, and loading conditions that need to be included in the engineering analysis. To create a BOD for a Lunar VTVL pad design, both Lunar environmental parameters, and anticipated loading conditions from the landing or launch vehicle need to be established. Once these parameters have been organized, an engineering analysis can be performed.

This research has organized a BOD for a hypothetical VTVL pad. Additionally, a Finite Element Analysis (FEA) has been performed for a 20-meter diameter pad exposed to an anticipated Human Landing System class lander rocket plume. The pad material has been evaluated using both concrete and ceramic structural materials. The FEA used pressure and heat flux applied from an anticipated plume to evaluate physical and thermal stresses generated during landing operations. Physical lander leg impact and static bearing loading has also been analyzed.

Figure 1 indicates example FEA results from this analysis. The contour depicted are total stress results from both physical downward pressure and thermal stress caused from a landing vehicle.

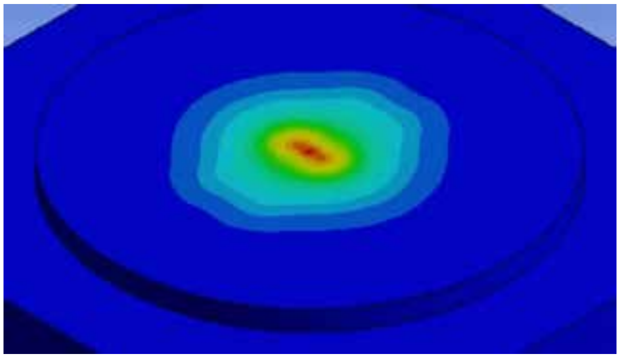


Figure 1: Example FEA results from total stress (pressure and thermal) of a landing vehicle.

Results from this analysis are being incorporated to produce generalized lunar landing and launch pad loading conditions to be provided in the "Lunar Design Loads" section of the American Society of Civil Engineer's (ASCE) "Lunar Infrastructure Engineering, Design, Analysis, and Construction Guidelines". A document being drafted by the ASCE Space Engineering and Construction Technical Committee.

References: [1] Carrier, D. et al (1991) The Lunar Sourcebook. [2] Chambers, W. A. et al. (2021). *Earth and Space 2021,* 22–31. [3] Clegg, R. N. and Jolliff, B. L. (2015). *Earth and Space 2014,* 131–139. [4] Ferguson, R. E. et al. (2018). *Earth and Space 2018,* 281–288. [5] Fontes, D. et al. (2022). *Acta Astronautica, 195,* 169–182. [6] Gale, M. et al. (2020). *AIAA Scitech 2020 Forum.* Orlando, FL. [7] Gelino, N. J. et al. (2021). *Earth and Space 2021,* 855–869. [8] Gelino, N. J. et al. (2023). *Earth and Space 2022,* 789–803. [9] Hintze, P. E., and Quintana, S. (2013). *Journal of Aerospace Engineering, 26(1),* 134–142. [10] Kelso, R et al. (2016). *PISCES and NASA Kennedy Space Center Project Update. Earth and Space, 15.* [11] Kuhns, M. et al. (2021). *Earth and Space 2021,* 1027–1032. [12] Kuhns, M. et al. (2021). *Earth and Space 2021,* 62–78. [13] Lee, J. et al. (2012). *Earth and Space 2012,* 128–134. [14] Mehta, M. et al. (2013). *AIAA Journal, 51(12),* 2800–2818. [15] Mishra, S. K. et al. (2022). *Planetary and Space Science, 211,* 105398. [16] Mueller, R. P. et al. (2016). *Earth and Space, 13.* [17] O'Konek, N. et al. (2012). *Earth and Space 2012,* 228–236.

Plume-Regolith Dust Cloud Characterisation

Claudia Jimenez Cuesta[1], David Pickles[1], Andrea Cammarano[1], Hossein Zare-Behtash[1]
[1]James Watt School of Engineering, University of Glasgow (c.jimenez-cuesta.1@research.gla.ac.uk)

Introduction:

One of the main challenges that spacecraft face during landing on extraterrestrial bodies is the regolith dispersion due to the nozzle exhaust plumes. Data from the Apollo missions showed that lifted particles can obstruct vision and damage hardware through sandblasting [1], an effect that was observed in the samples returned from the Surveyor III. To safely design future crewed landers to the Moon and beyond, which will inevitably require a greater payload, it is essential to have a deeper understanding of the phenomena surrounding plume and dust interactions, such that measures can be taken to prevent/reduce damage and adverse affects. This field of study, referred to as Plume Surface Interactions (PSI), has been the focus of attention in recent years. Many researchers have aimed to simulate these interactions through a combination of continuum and rarefied gas flow solvers [2,3,4] however, proving their validity has been difficult due to the lack of measurements.

At the University of Glasgow, a large volume dirty vacuum chamber has been designed in collaboration with ESA-ESTEC to simulate extraterrestrial landings. At this unique facility, high-speed imaging will be used to observe the dust cloud developed upon plume impingement, such that PSI can be characterised, which will inform the design of robust landing systems that are regolith resistant.

Moreover, considering that establishing long-term presence in the form of habitats on the Moon is reliant on achieving environmental management, the control of plume-regolith interactions will be paramount in this regard. This research will also be essential when designing In-Situ Resource Utilisation (ISRU) systems requiring dust contamination resiliency to avoid problems such as abrasion, clogging, and seal failures, to name a few.

Facilities:

The dirty vacuum chamber at the University of Glasgow (see Figure 1) is comprised of a test section with a volume of approximately 12 m^3 and is able to reach an ultimate vacuum level of 1 Pa. The total volume of the vacuum facility is just over 70 m^3, which also includes a buffer tank. A custom-designed heat exchanger, simulating exhaust plumes, has been designed and a range of regolith simulants will be tested.

Figure 1: Vacuum chamber

Experimental setup:

To capture the dust cloud produced upon impingement of the plume onto the test bed, multiple high-speed cameras will be placed at different orientations, as shown in Figure 2. Edge detection will be carried out for different levels of dust concentration and plume firing lengths.

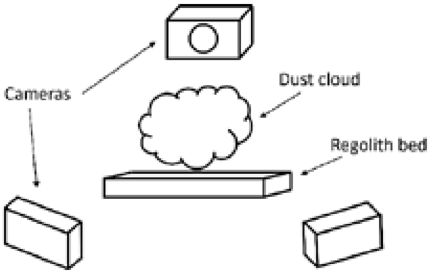


Figure 2: Experimental setup

References:

[1] P. T. Metzger et al. (2008) Cratering and blowing soil by rocket engines during lunar landings, *International Conference on Case Histories in Geotechnical Engineering.*

[2] H. Zhang et al. (2022) The investigation of Plume-Regolith Interaction and dust dispersal during Chang'E-5 descent dtage, *Aerospace, 5, 358*.

[3] A. Rahimi et al. (2020) Near-field plume-surface interaction and regolith erosion and dispersal during the lunar landing, *Acta Astronautica, 175, 308-326*.

[4] A. B. Morris et al. (2015) Approach for modeling rocket plume impingement and dust dispersal on the moon, *Journal of Spacecraft and Rockets, 52, 362-374*.

A New Icy Lunar Regolith Simulant: Pressure Fused Granular (PFG) .

D. K. M. Johnson[1] and C. B. Dreyer[2], et al. [1]Colorado School of Mines, dkjohnson@mines.edu [2]Colorado School of Mines, cdreyer@mines.edu

Introduction: A novel type of icy lunar regolith simulant, called pressure fused icy lunar regolith simulant, or PFG for short, has been created in the Colorado School of Mines Center for Space Resources. This icy regolith simulant differs from other icy regolith simulants in that liquid water never comes in contact with regolith grains during the production process, and can be tuned to exhibit a wide range of mechanical properties. One of the most common methods used to produce icy regolith simulants involves mixing liquid water with a regolith simulant, compacting the mixture, and freezing it [1, 2]. While this method is easy to produce at scale, it cannot produce homogeneous ice-regolith mixtures above about 13 to 17 wt. % water, which is the saturation point of the regolith simulants used [1,2]. At higher water contents, the material properties of the material are similar to limestone [1,2].

Production Method:
To produce PFG, first water is frozen, then passed through an ice shaver. The resulting mixture is then sieved to a size of 500 μm or less. These ice particles are then mixed with chilled CSM-LHT Lunar regolith simulant. The resulting mixture is called granular icy regolith simulant, or granular for short. It exhibits very little bearing strength, similar to low density dry regolith simulants. To produce PFG, granular is placed in a container, then pressed with a piston at a desired applied isostatic pressure for a duration of 10 minutes. This compacts the mixtures and bonds it together.

In Figure 1 Ian artist's rendering of the two types of icy regolith simulant produced at the School of Mines can be seen. In the image to the left, granular icy regolith is seen with discrete regolith and ice grains. After pressure is applied, these discrete ice grains pressure form into the regolith grains and eachother, bonding the material together into a structure.

Figure 1: On the left, granular icy regolith is shown, and on the right PFG is shown as the result of granular icy regolith being pressed until the ice particles bond with the regolith particles and eachother. Credit: Kevin Cannon

Results and Conclusion: PFG samples were produced with varying amounts of applied pressure and water content. Samples were produced with 0, 2, 5, and 10 wt. % water content, and with applied isostatic pressures of .133, .233, .531, and .797 MPa. For each test condition, at least 3 samples were produced, then penetration resistance was measured using a 10 mm diameter flat head penetrometer.

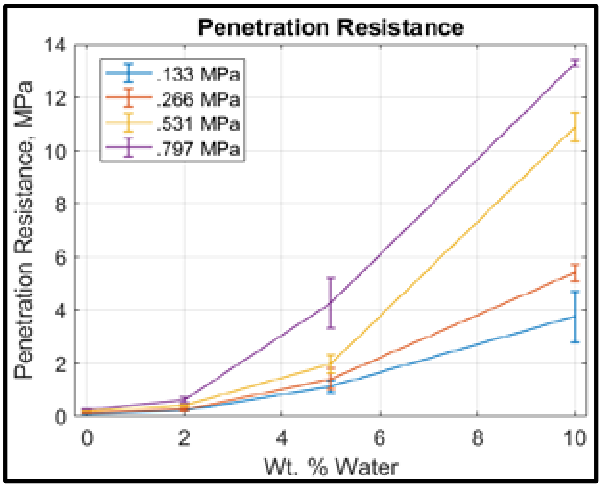


Figure 2: Penetration resistance of PFG vs. the weight percentage of water content. Included are curves with different applied pressures. Error bars are +/- 1 standard deviation.

As can be seen in Figure 2, as water content increases, so does the simulant's capacity for penetration resistance; however, it should be noted that a sample with lower water content can have a higher penetration resistance than one with higher water content if greater pressure is applied. In this way, PFG is tunable to a wide range of strengths for a given water content simply by varying the applied pressure. Since the precise morphology of ice in lunar PSRs is unknown, PFG may be more likely than other simulants to be able to replicate lunar conditions.

References:

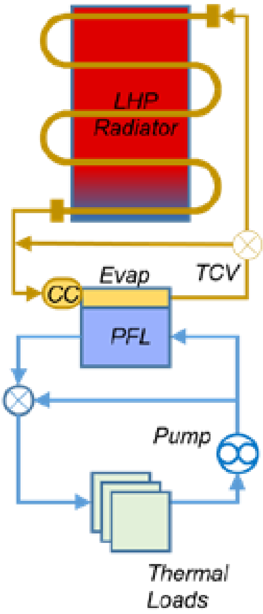
[1] Pitcher C. and Komle, N. et al. (2015). Advanced Space Research. Investigation of the Properties of Icy Lunar Polar Regolith. [2] Gertsch L.. and Gustafson R. et al. (2006) *Effect of Water Ice Conente on Excavatability of Lunar Regolith,* AIP, 1093-1100

Hybrid Thermal Control System for Extreme Thermal Environments. W. E. Johnson[1], R. G. Schunk[1], K. E. Daniel[1], and J. T. Farmer[1], [1]NASA Marshall Space Flight Center, 4487 Martin Rd, Huntsville, AL 35812. (Contact: William.e.johnson-1@nasa.gov)

Introduction: NASA's return to the moon brings about many challenges, including issues with survival on the Lunar surface. In order to be sustainable, assets such as landers, rovers, and habitats must be usable for more than a single mission duration. One of the key challenges with sustainability is designing adequate thermal control systems that allow for surface systems to survive both during the day and the Lunar Night.

The extreme thermal environments on the Lunar surface are a challenging design space for thermal engineers. At equatorial regions the Lunar noon can be very hot, requiring systems with high heat rejection to the environment. At polar regions, such as those targeted by the return to the moon, the daytime temperatures are more moderate. During the Lunar night, however, temperatures plummet and can approach -200 degrees Celsius. Such temperatures are formidable and require specialized thermal control systems to allow surface assets to surface the long night.

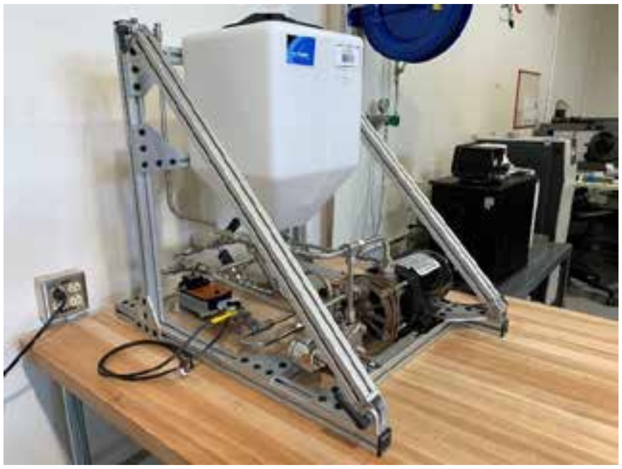
Hybrid Thermal Control System: Marshall Space Flight Center (MSFC) has been developing a hybrid thermal control system that can be utilized for various surface assets that must survive in extreme lunar environments. This scalable system is targeted for human-rated systems and utilizes a combination of a pumped fluid loop and a loop heat pipe (LHP) with thermal control valve (TCV).



Pumped fluid loops (PFL) have a long heritage of use in human rated systems. They can collect large amounts of waste heat and transport it over long distances in rovers, habitats, and other systems. By utilizing a non-toxic working fluid in the habitable volume the PFL is easily serviceable by the crew and does not pose a risk during any unexpected leaks or failures.

The addition of a LHP for the exterior heat transport and rejection adds several benefits to the system for extreme environment survival. The quantity of LHPs can be tailored to optimize heat rejection for different systems and allows for large radiative surfaces. By utilizing a TCV in combination with the LHP, there can be high heat transfer during the daytime with minimal heat transfer during the night. The TCV passively controls the amount of heat transfer through the LHP.

Prototype Development and Testing: A prototype PFL has been fabricated and tested at MSFC. This PFL allowed for checkout testing of the pump, sensors, and valves necessary to operate and monitor the system.



This prototype PFL has been integrated with a LHP manufactured by Advanced Cooling Technologies. The combined system was tested at MSFC to characterize heat transfer and control capability. The LHP was placed in a thermal vacuum chamber with the PFL in the adjacent ambient environment. Heat was input to the PFL to simulate waste heat. The PFL flows through a heat exchanger attached to the LHP evaporator to transfer heat between the system. Results from the ambient and thermal vacuum tests will be presented, with a comparison to representative traditional systems.

The Effects of Surface Composition and Temperature on Simulated Lunar Radiance Spectra.

Eshaan Ram Kaipa, Evergreen Valley High School, San Jose, CA, 95148.
eshaankaipa@gmail.com

Investigating and exploring the electromagnetic radiation spectra produced from Lunar surfaces and landscapes is a branch of Lunar Spectroscopy that has grown in interest over the past decade. The Moon's geological and mineralogical study is one such attribution to the implementations of Lunar Spectroscopy. In the past, missions such as the Lunar Reconnaissance Orbiter (LRO) and the Lunar CRater Observing and Sensing Satellite (LCROSS) have uncovered data suggesting the presence of water-ice on the Moon, a critical resource for terraforming and further space undertakings. Still though, deployable technology that enables scientists and researchers to analyze complex data of Lunar radiance spectra is primitive in performance and reliability, nonetheless complex and expensive. Thus, applications of Lunar Spectroscopy research in correspondence to the Moon's physical composition are relatively new and unexplored. Besides understanding the geological history of the Moon's surface, methodologies for efficient in-situ resource utilization are required. Hence, the primary motivation for this research is diagnosing the relationships that temperature and composition have on Lunar radiance spectra. Accordingly, in this paper, the properties of Lunar radiance spectra between the 1-15 µm wavelength range is explored using NASA's Planetary Spectrum Generator (PSG) tool by varying the surface composition and surface temperature parameters.

Planetary Spectrum Generator (PSG) is an online tool developed and supported by NASA. This tool can produce a model radiance spectrum for any planetary configuration through auto generated .txt files, significantly useful for Lunar Spectroscopy research purposes. The prominent features of PSG are its three primary settings: Object, Composition, and Instrument. Object accounts for the planet/star, Composition accounts for the minerals and temperature of interest, and Instrument accounts for the lens, wavelength, and unit of energy. The tuning of these three settings allows for the radiance spectra of essentially any space body to be obtained.

Accordingly, an application programming interface (API) using Python script was developed to work in conjunction with PSG. The API's call initializing the computer's txt files allows for the overlay plotting of multiple spectra. Hence, a variety of model configurations of the Moon were analyzed, and surface radiance spectra were extracted within the selected 1–15 µm range over surface temperatures on a scale of 140 ^{0}K to 400 ^{0}K that is practical for Lunar exploration. This temperature range represents average day-night temperature fluctuations on the Lunar surface.

Using the custom API, minerals and materials that were characteristic and abundant on the Moon's surface such as oxides, silicates, metals were investigated. Examples of specific compositional materials that were analyzed include Olivine, Basalt, Pyroxene, and Silicate. The analysis of surface compositional configuration versus surface temperature and their relationship in producing Lunar radiance spectra was carried out. Figures 1 illustrates temperature tuning of pyroxene spectra. Because the radiance spectra is characterized by a mineral dependent (solar) and temperature dependent (thermal) component, it is feasible to first tune the mineral abundances then tune temperature, as illustrated in Figure 2. It was found that the material composition is dominant for the shorter 1-3.5 µm wavelength range, also known as the solar wavelengths, and the temperature controls the characteristics of the longer wavelength. Additionally, the results yielded and suggested key features of the minerals themselves, such as the fact that Olivine has a greater reflectance than Silicate, which is acutely duller.

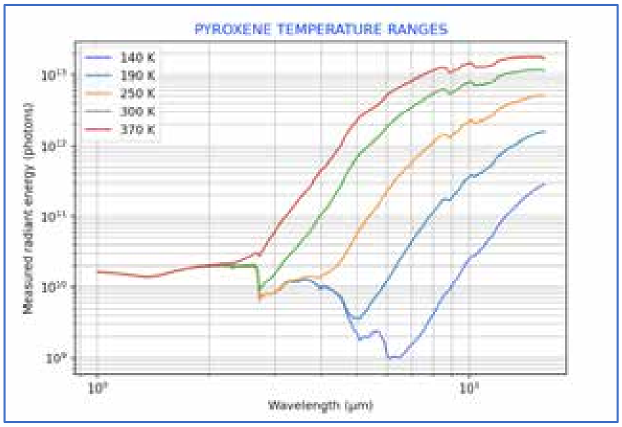


Figure 1. Temperature tuning of pryroxene spectra.

.

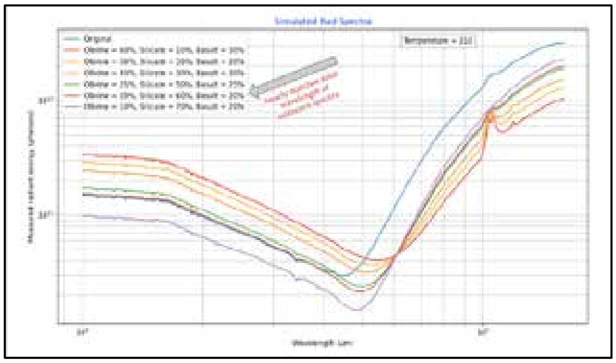


Figure 2. Tuning the mineral abundances until a near perfect solar wavelength is achieved.

The next phase of investigation is to create a model that can automatically classify the minerals present within a given radiance file. Furthermore, the PSG's mineral datasets will be analyzed through Machine Learning algorithms to extract valuable information on radiance spectra and support sensor architecture development for future Lunar missions. This work was carried out in collaboration with NASA Goddard Space Flight Center and the University of Maryland.

Lunasonde: Cartographers of the Space Age. H. KLING and T. PREJEAN[i]

Introduction: Lunasonde was founded to make the underground world visible, transforming humanity's approach to subsurface exploration and resource extraction while pioneering sustainable access to the subsurface. Lunasonde is building an interactive, three-dimensional map of features below the surface of the Earth, and eventually the Moon, Mars, asteroids, and beyond. Using low-frequency ground penetrating radar, Lunasonde can reveal the subsurface with a metamaterials-based technology developed by founder and CEO, Jeremiah Pate (Figure 1).

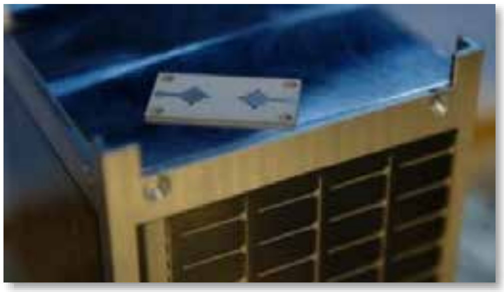


Figure 1. Lunasonde's miniaturized metamaterial-based antenna in relation to a 1U CubeSat.

Portal to the Subsurface: After field testing on Earth, Lunasonde is developing high-fidelity tomographic maps of the Earth's subsurface up to 10 kilometers underground by implementing the metamaterial on a space-based platform, resulting in scalable, reusable, and sustainable technology. Lunasonde's team of data scientists generate the data visualizations and insights that will be available in narrative and interactive digital formats for the end user (Figure 2). The data product pricing is flexible and customizable depending on multiple factors such as the size of the coverage area, resolution of the images, type of resources explored, and frequency of reports. Lunasonde's technology extends observation to the subsurface, allowing access to a previously untapped dataset; this approach will enable imaging of the underground world at scale for the first time.

Terrestrial Traction: Lunasonde's customer engagement strategy has evolved into contractual discussions with early pilot customers. Lunasonde's current contracts include a major mining conglomerate, a partnership with a resource investment company focusing on ethical and sustainable assets, and a Fortune 500 company. Additionally, Lunasonde has engaged with smaller, local projects for initial tests. Lunasonde's team recently completed a customer project for detecting underground anomalies in the U.S. Southwest and in 2023 will be surveying an area of interest for a copper mining company.

Detecting Lunar Resources: With a strong foundation built on subsurface Earth imaging, Lunasonde aims to be a part of the community of engineers, scientists, and innovators planning and developing infrastructure on the Moon and beyond. Out of the LSIC discussions it became clear that subsurface understanding of the Moon is crucial to construction and infrastructure development as lunar exploration becomes more accessible. Lunasonde proposes to be the spearhead of lunar subsurface imaging and understanding to contribute to the exploration of the Moon. Data acquisition is a core part of Lunasonde's pathway to commercialization. Lunasonde's ability to adapt algorithms to identify numerous subsurface resources allows exponential datasets to be available to customers. With flexibility and adaptability built into Lunasonde's business plan, the company can grow exponentially as space technology and resource exploration accelerates in the near future.

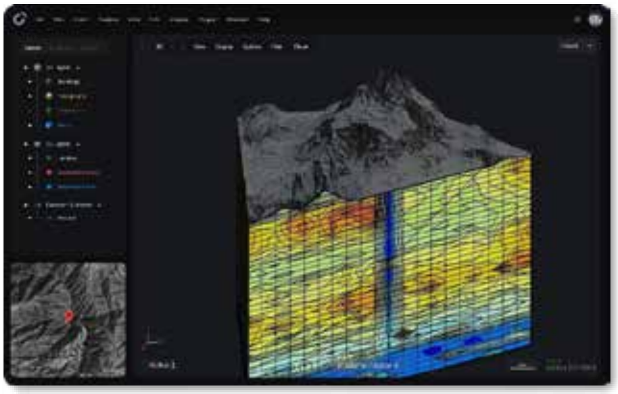


Figure 2. A proposed render of Lunasonde's user interface.

---

[i] Haleigh Kling, haleigh@lunasonde.com. Tristan Prejean, tristan@lunasonde.com. 900 19th St. Washington, D.C. 20006.

LUNAR CARGO. C. S. Kosmas[1], LUNAR CARGO P.C., 19 El Venizelou Ave, Ilioupolis 16343, Greece, (Contact: charis.kosmas@lunarcargo.space)

Introduction: Two concepts under development, that can accommodate oversized cargo and parcels. They can reduce the cost of lunar landings by up to 70%. Ovesized cargo to be delivered by a wheel-shaped spacecraft named OPLONAS and parcels by a surface-based parcel-capturing system called MACEDONAS. No fuel is required for the landing. OPLONAS's material are up-cycled for providing a habitat and construction material for a MACEDONAS or other woven or tethered constracts.

OPLONAS: (**O**versized **P**ayload **L**ander **O**n **N**on-**A**tmospheric **S**omata).

It consist of a cylindrical payload hub (6 m D , 9 m H), which is surrounded by axialy extended ropes, that hold in place a flexible rim. The rim maintains rigidity due to centrifugal forces. OPLONAS is spinned up before touching the surface to minimize displacement friction to tolerable levels. The dissipation of the kinetic energy is effected by roll friction. OPLONAS ideal landing area is Oceanus Procellarum.

Fig 1: OPLONAS

MACEDONAS: (Momentum Absorption **C**atcher for **E**xpress **D**eliveries of **O**n-**N**on **A**tmospheric **S**omata) is a lunar surface based parcel catcher, that can arrest, decelerate and steer the parcels to land smoothly on a safety net. Recent developments call for exploitation of a new antiballistic material "**Talin Shock Absorbing Material**" (TSAM). that protects the parcel from deformation and simplifies the caching apparatus configuration.

An orbiter spacecraft ejects regularly parcels, targeting the (one or more) catcher(s), successively

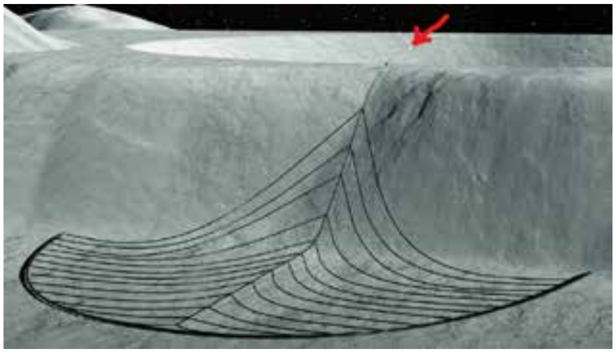


Fig 2. Parcel on its way to enter the catcher

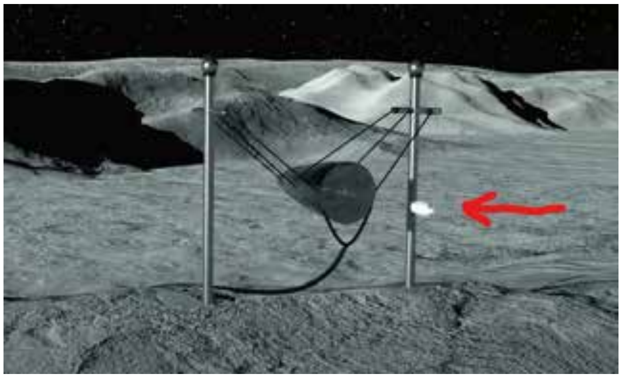


Fig 3. Parcel about to enter the catcher

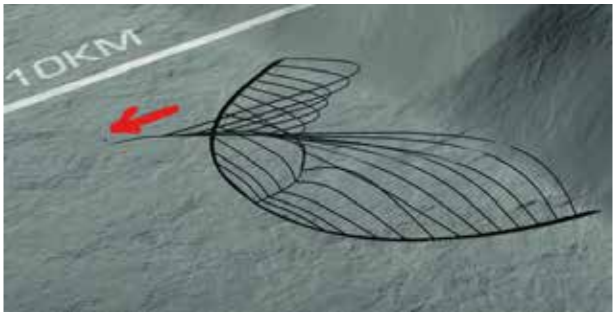


Fig 4. Catcher, decelerates the parcel

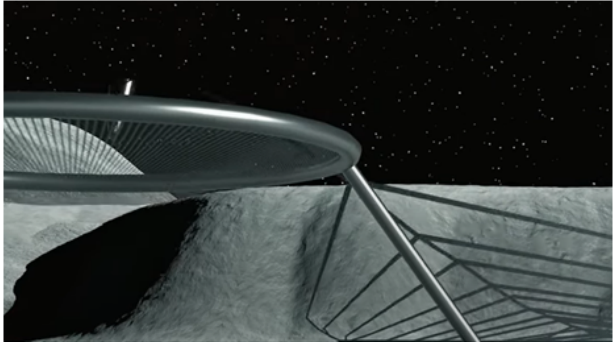


Fig 5. Catcher lands at the safety net

Production of Solar Arrays from Lunar Materials. G. A. Landis, NASA John Glenn Research Center, 21000 Brookpark Road, m/s 302-1, Cleveland, OH 44135. geoffrey.landis@nasa.gov

Introduction: One proposed use of lunar resources is as raw materials for manufacturing solar arrays, which could be used to increase the availability of electrical power for living, exploring, and for industrial production on the moon, as well as possibly, in the future, producing power to use elsewhere in space and on Earth [1].

Materials required: By mass, the solar cell itself is not the main component of the mass of materials needed for solar array manufacture. In addition to the semiconductor, a typical array requires glass, front- and back- ohmic contact metallization, substrate, wiring, and physical structure[2].

Glass. Glass is used to protect the solar cell from the space environment, most significantly, from damage due to ambient particulate radiation. The most significant requirement of the glass is that it must be transparent. This requires that the trace impurities of transition metals (primarily iron), which cause color centers darkening the glass, be extremely low. Since iron is a major component of lunar surface material, this requires refining the materials after reduction. A secondary concern is that the thermal expansion coefficient of the glass be near to that of the solar cell.

Metals. Aluminum, abundant in lunar regolith, is the clear choice for the wiring, since it is an excellent electrical conductor and easily formed into wires. Since the environment lacks oxygen, calcium is a possible choice for wiring as well, with good conduction properties. Aluminum may also be used for the structural material of the array.

Semiconductor. Of the semiconductors from which photovoltaic cells can be made, silicon is the clear choice if cells are to be made strictly from material available on the moon. While multijunction III-V solar cells have significantly higher efficiency and radiation tolerance, the materials required for these (gallium, arsenic, indium, phosphorus, and germanium) are not abundant in lunar regolith. Silicon solar cells can be made in either single-crystal or thin-film form, with higher efficiencies achieved with single-crystal, at the price of a much more complicated manufacturing sequence, requiring crystal growth and wafering; while thin-film silicon deposition can be done onto a foreign substrate (or superstrate). Like the coverglass, such a substrate will need to be closely matched in thermal expansion coefficient to the deposited silicon.

In thin-film cells, the semiconductor itself will only be a few micrometers in thickness, a negligible portion of the mass of the array. Thus, it would be reasonable to use material brought from Earth for this purpose. Of thin-film semiconductors used in solar arrays on Earth today, Copper Indium-Gallium Selenide (CIGS) and Cadmium Telluride (CdTe) are reasonable choices. Perovskite-based solar cells, although less well developed, may also be a choice due to ease of deposition.

Refining of Regolith: Production of these materials requires collecting the raw materials, in this case lunar regolith, consisting primarily of silicates. The silicates area then reduced to remove the oxygen, and the remaining material, consisting of metals and silicon, refined to produce the pure metals and silicon, with low values of impurities. Oxygen is produced as a valuable byproduct, useful for both breathing oxygen and for rocket propellant. To produce silicate glass, oxygen is then reintroduced to the refined silicon and select metals.

These processes are done at high temperature. A solar furnace is one possible method of producing such temperatures, but has a disadvantage that evaporated and redeposited material can degrade mirror performance very quickly, and hence an electric furnace (powered by solar arrays) is preferred. A significant difficulty in this process is minimizing the temperatures required in the reduction and refining. This is required partly to reduce the energy required, but also because high-temperature processing typically requires frequent replacement of parts, such as electrodes.

The proposed process is calcium-thermal reduction to break the silicon-oxygen bond in the input silicate materials, followed by an electrolysis, where a molten calcium chloride/calcium oxide mixture with a eutectic point of 750 °C is chosen as a flux to reduce processing temperature. The calcium is replenished using Ca refined from the lunar material. Details are given in refs [3] and [4].

References: [1] Landis G.A. and Perino M.A. (1989) “Lunar Production of Solar Cells: a Near-Term Product for a Lunar Industrial Facility,” *NASA TM-102102* [2] Landis G.A. (2005) “Materials Refining for Solar Array Production on the Moon,” *NASA TM-214014* [3] Landis G.A. (2014), "Resource Production on the Moon," *Space Resources Roundtable/Planetary & Terrestrial Mining Sciences Symposium* [4] Landis G.A. (2011) “Calcium Reduction as a Process for Oxygen Production from Lunar Regolith,” AIAA-2011-701, *49th AIAA Aerospace Sci. Conf*.

A Common Approach to Overcoming the Lunar Dust Challenge

A. G. Lillard[1], [1]Lockheed Martin, Contact: austin.g.lillard@lmco.com

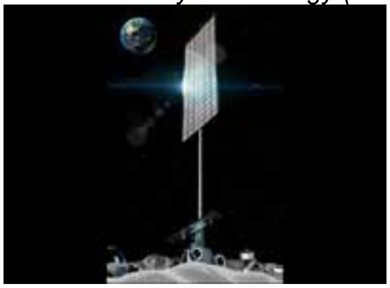
Introduction: Lockheed Martin is in the process of developing several lunar solutions to enable the future of the lunar economy. Lunar dust is expected to be a challenge for all lunar surface vehicles, with impacts to many areas of system operation. By identifying challenges across a variety of vehicles, common solutions can be leveraged to mitigate the dust risk.

Vehicle Overview: Several vehicles are being developed for operation on the lunar surface:

Lunar Mobility Vehicle (LMV)

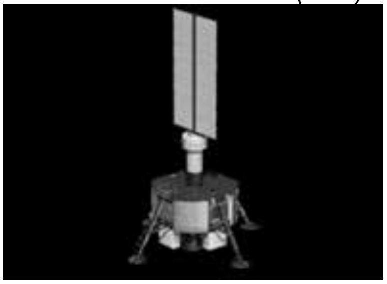
LMV provides both uncrewed and crewed transport on the lunar surface. This enables science collection and lunar infrastructure build up.

Vertical Solar Array Technology (VSAT)



VSAT provides large-scale solar power generation on the lunar surface, enabling other vehicles to leverage it as a power source.

Surface Fission Power (SFP)



FSP provides nuclear power generation on the lunar surface, eliminating the dependency on sunlit regions. This enables other vehicles to leverage FSP as a power source, and increases location flexibility.

Common Dust Concerns: Although each vehicle serves a different mission purpose, affects several common areas of design. An overview of these dust concerns are shown below:

- Mechanical
  - Gimbals
  - Actuators
  - Motors
  - Connectors
  - Material Degradation
- Power
  - Solar Array
- Thermal
  - Radiator
- Sensors
  - Autonomy Optics
  - Navigation Optics

Common Dust Solutions: A wide variety of solutions are being considered to address the problems listed above. These solutions include:

- Operational/Architectural
  - Dust Transportation Management
  - Lander Plume Management
  - System Deployment Management
- Passive
  - Material Selection
  - Covers
  - Coatings
  - Seals
  - Electrical Connectors
- Active
  - Electrodynamic Dust Shield
  - Vibration
  - Mechanical Removal
  - Compressed Gas

Conclusion: With the increase of activity on the lunar surface, mitigating the effects of lunar dust on vehicle operations becomes necessary. By identifying similarities between vehicles and leveraging NASA roadmaps and initiatives, common solutions are being investigated to solve the lunar dust problem. System interactions and integrated operations on the lunar surface should also be considered. Given these challenges and considerations, LM will present on the common areas of concern for the lunar platforms described and what solutions are being considered for each area.

RIDER: An Open-Access Lunar Terramechanics and Rover Wheel Testbed. J. Long-Fox[1], M. P. Lucas[2], J. Conway[1], A. Glover[1], S. Kline[1], M. Conroy[1], A. Madison[1], P. Easter[1], A. Hacker[1], G. Blandin,[1] H. M. Sargeant[1], C. Neal[2], D. Britt[1] [1]University of Central Florida CLASS Exolith Lab (4111 Libra Drive Room 430, Orlando, FL 32816; jared.long-fox@ucf.edu), [2]University of Notre Dame Department of Civil and Environmental Engineering and Earth Sciences, 156 Fitzpatrick Hall, Notre Dame, IN 46556.

Introduction: Lunar exploration and infrastructure development requires safe and efficient locomotion to transport supplies, resources, and personnel, but there are no open-access facilities in which to quantitatively test rover wheels to study planetary terramechanics. The Regolith Interactions for the Development of Extraterrestrial Rovers (RIDER) testbed (Figure 1) offers the lunar science and engineering community the capability to research, develop, and test mobility systems by simultaneously addressing challenges posed by both the lunar surface and rover design. RIDER systems include a 3.8 m long, 0.9 m wide, and 0.5 m deep simulant bin with dust mitigation, air filtration, illumination, and video systems. RIDER provides researchers with quantitative data on wheel efficiency (motor drive current, slip, sinkage) and geotechnical properties of the high-fidelity regolith simulants used in testing.

Figure 1. RIDER at the University of Central Florida (UCF) Exolith Lab.

Simulating the Lunar Surface with RIDER: When studying lunar terramechanics or designing lunar rovers, the use of appropriate simulants is critical. The physical properties of lunar regolith are primarily determined by the local mineralogic composition, particle size distribution, and level of compaction [1]. RIDER, housed in Exolith Lab, has access to world-class simulant production facilities and hence is able to use high-fidelity simulants with custom mineralogies and particle size distributions that can be compacted to create custom density profiles in the testing bin. Lunar trafficability is also impacted by the reduced gravity and lack of atmosphere. To address these challenges, RIDER is equipped with a load application/gravity offload system as well as an industrial dehumidification unit to reduce ambient moisture and keep the simulant as dry as possible since moisture content alters simulant physical properties [2].

Simulating Lunar Rovers with RIDER: The properties of local regolith set the baseline for lunar trafficability, so rovers must accommodate regolith conditions for efficient and safe travel. Since there are not yet stadards for rover wheel size, design, mounting mechanisms, or drive systems, RIDER has been developed to accommodate a wide range of rover wheel geometries, mounting systems, and motor torque and speeds. This flexibilility is enabled by a dust-tolerant motor box with a heavy-duty wheel hub and custom adapters to interface with customer wheels. RIDER has motors with different gear ratios and ranges of rotational velocities provide customers with the ability to evaluate wheel performance as a function of drive specifications. The load application system allows single wheel loads of ≤200 kg to be tested on wheels with diameters from 26 cm to 82+ cm. The initial testing campaign in RIDER includes a replica Lunar Roving Vehicle (LRV) wheel, a VIPER-like wheel, & an Astrobotic Polaris prototype rover wheel [3].

Conclusion: RIDER uses an integrative, multidisciplinary approach to enable the scientific and engineering communities solve problems in lunar mobility through the simultaneous evaluation of terramechanics contributions from both the lunar surface and from rover designs.

Acknowledgements: RIDER is supported by the NASA SSERVI Center for Lunar and Asteroid Surface Science (CLASS; NASA Cooperative Agreement 80NSSC19M0214) in collaboration with the University of Notre Dame. Special thanks to Colin Creager (NASA Glenn Research Center) for the loan of the LRV and Resource Prospector wheels, and to Mike Provenzano (Astrobotic) for the loan of the Polaris prototype wheel.

References: [1] Carrier D. W. et al. (1991) *The Lunar Sourcebook Ch. 9*. [2] Long-Fox, J. et al. (2022) *ASCE Earth and Space Conference*. [3] Lucas et al. (2023), *54th LPSC Abstract #2463.*

WORMS: Field-reconfigurable multi-robots for extreme lunar terrain access.

G. Lordos[1], M. J. Brown[1], J. Rodriguez[1], K. Latyshev[1], A. Liao[1], S. Shah[1], C. Meza[1], B. Bensche[1], C. Cao[1], Y. Chen[1], A. S. Miller[1], A. Mehrotra[1], A. Mokkapati[1], T. Cantu[1], K. Sapozhnikov[1], J. Rutledge[1], F. Zaman[1], S. Reyes[1], C. O'Neill[1], C. Rissola[2], D. Rivero[1], P. Mahesh[1], D. Trumper[1], S. Kim[1], O. de Weck[1], J. Hoffman[1], W. Chun[3] [1]Massachusetts Institute of Technology, 77 Mass. Ave., Cambridge, MA 02139; [2]Carnegie Mellon University, Pittsburgh PA 15213; [3]University of Denver, Denver CO 80208. (Contact: glordos@mit.edu)

Introduction: Before and after the planned Artemis III moon landing, there will be a need for a variety of robots to support extreme lunar terrain mobility for science, exploration, and infrastructure development. However, rovers with flight heritage are based on wheeled architectures and are not designed for extreme terrain. Moreover, absent prior coordination, NASA and its international and commercial partners may end up giving rise to a zoo of incompatible and overspecialized robots for multiple different extreme terrain access use cases such as lava tubes, pits, permanently shadowed regions, steep inclines or highly porous terrain. The 2022 NASA BIG Idea Challenge selected teams to develop extreme lunar terrain mobility technologies and MIT proposed and demonstrated the Walking Oligomeric Robotic Mobility System (WORMS) platform for field-reconfigurable multi-robots.

Field-reconfigurable robotics platform: The elements of the WORMS architecture include (1) identical articulating Worm robots (2) simple Accessories, such as shoes and chassis or pallets, as well as (3) more sophisticated Species Modules with specialized sensing or actuating capabilities. These elements can be integrated in different ways into various larger robot forms tailored to multiple missions and even repaired in the field by simply replacing modular elements and rebooting. Each known robot configuration requires only hardware elements plus software, meaning that new robot designs can be transmitted to the Moon, subject only to having Worms, Accessories, and Species Modules in stock at Artemis Base Camp. The platform is an open architecture designed for flexibility, easy operability, and simplicity in field maintenance and operations by non-specialists.

Design: Design exploration considered a large range of potential missions for walking robots and took inspiration from animals to conceptualize alternative locomotion strategies and associated novel robot forms. The findings from design exploration were synthesized into the proposed field-reconfigurable WORMS lunar robotics platform architecture [1,2]. This reconfigurable robotic architecture is enabled by three key technologies: a robust universal mechanical interface, power sharing between robots, and multi-agent autonomy to coordinate motion of the assembled robot. Each element of the architecture has at least one Universal Interface Block (UIB), which allows elements to be easily reconfigured. Power sharing extends the usable range of assembled robots. WORMS' multi-agent autonomy, implemented using ROS2 nodes, provides a flexible platform for coordinating motion among independent robots. These elements are incorporated into articulating "Worm" robots. The ~10 kg, ~1 m long prototype Worm is the design's first generation. Future Worms will be scaled (20 kg and ~1 m for Gen 2 and 60 kg and ~1.5 m for Gen 3) to increase lunar payload capacity from kilograms to tons, simplify UIB disconnection for astronauts, and add autonomous assembly.

Testing and Validation: A prototype consisting of 6 Worm robots, 7 Accessories, and one Species Module was built and demonstrated in November 2022 [3,4]. This prototype has undergone 17 integrated tests to validate all key enabling technologies. Of note, the UIB was loaded to >130 Nm, a Worm's leg motion was powered using a common power bus shared by 6 Worms, and the multi-agent autonomy software coordinated walking for the hexapod on level ground [2, 4].

Impact: We propose that WORMS is a resilient, easily maintainable, low-cost, flexible, evolvable, future-proof, open, and modular architecture for the rapid field assembly of robots to support extreme terrain access and lunar infrastructure development. WORMS can prevent the emergence of an ungovernable robot zoo on the moon and support many of the robotic mobility needs of NASA and its commercial and international partners throughout the Artemis program and on to Mars and beyond.

Acknowledgments: see ref [1,2,3]

References: [1] Lordos G. et al. (2022) AIAA 2022-4395. [2] Lordos G. et al. (2023) IEEE Aero [3] Lordos G. et al. (2022) BIG Idea Challenge Forum [4] https://youtu.be/U72lmSXEVkM

MoonFibre - Development of the Manufacturing of Fiber-based Products on the Moon from Regolith.

Niecke A.[1], Lüking A.[2], Gries T.[1], Kalapis S.[3], Schröder K.-U.[3]
[1]Institut für Textiltechnik RWTH Aachen University, Germany, alexander.niecke@ita.rwth-aachen.de,
[2]FibreCoat GmbH, Aachen, Germany, alexander.lueking@fibrecoat.de
[3]Institut für Strukturmechnaik und Leichtbau RWTH Aachen University, Germany
Contact: alexander.lueking@fibrecoat.de

Introduction:

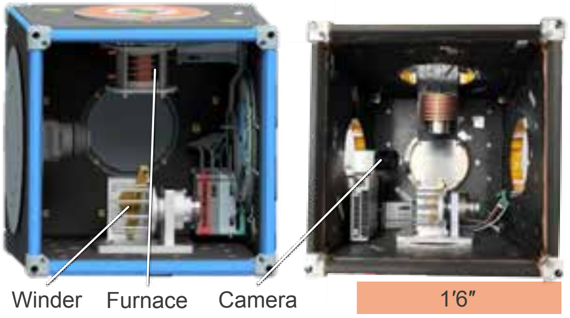
With > 250 missions planned over the next 10 years, the Moon is increasingly becoming the focus of research and also industry. [1] The use and processing of raw materials (ISRU) on the Moon has the potential to save $1.5M per kilogram by eliminating transportation costs from Earth. [2] To fully realize the potential, as many critical infrastructure products as possible should be made from lunar regolith. [3] Critical infrastructures are dust repellent and at the same time structurally strong landing pads, paths or structures. Therefore, plans exist worldwide to sinter or 3D print lunar regolith on site. However, all ISRU approaches still have existing deficiencies in terms of properties and thus potential applications. For example, tensile strengths of only 40 MPa are achieved. Dust-reducing or even dust-repellent ISRU products cannot be realized by 3D or sintered materials either. It is therefore essential to develop materials that fully exploit the potential.

Fibers and textiles made from lunar regolith can unlock this potential and also significantly expand the possibilities for necessary products for lunar exploration. Glass and basalt fibers are commercially available on Earth. With up to 4,000 MPa, they are 100 times stronger in tensile strength than 3D or sintered materials. [4] At the same time, textiles offer the possibility of ISRU filter materials, insulators, or structural elements. For example, landing pads can be created from fiber mats, which prevents lunar dust from being stirred up. But also paths for rovers and astronauts made of fiber mats are possible.

Manufacturing MoonFibre on the surface:

In order to fully understand the potential of fiber materials, extensive studies have been carried out. First, the spinnability of various lunar simulants was examined theoretically from a physical point of view. The viscosity behavior of molten regolith was considered and an optimum processing temperature of 1.222 °C was determined. The lunar simulant was then heated to the processing temperature and filaments were produced at speeds of 800 m/min. The filaments, as shown in the figure, have a diameter of 16 - 18 µm. The tensile strengths of 1,600 MPa are 40 times higher than other ISRU approaches.

At the same time, an automatic production concept for the moon was developed. With an induction furnace, 16 kg/24 hours can be produced with only regolith and electrical energy.



Acknowledgment: MoonFibre is funded by German Aerospace Center DLR.

References:

[1] Chavers, G., Suzuki, N. & Smith, M. (2019). NASA's Human Lunar Landing Strategy. 70th International Astronautical Congress. Washington, D.C., USA

[2] E. Mahoney, In-Situ Resource Utilization. [Online]. Available: https://www.nasa.gov/isru (accessed: Dec. 19 2019).

[3] Panajotovic S., Meinert T., Becker T., A Arañó Romero J. C., Lüking A., "MoonFibre - Fibres from Lunar Regolith," in 18th Space Generation Congress, Washington DC, 2019. [Online].

[4] Gutnikov, S. I., Lazoryak, B. I. (2019). Effect of Nozzle Diameter on Basalt Continuous Fiber Properties. Advances in Glass Fibers, vol. 7. no. 7

Methodologies for Damage Quantification Due to Meteoroid Impacts on Lunar Habitats: A Design Perspective. S. Vaidya[1] and R. B. Malla[2], [1]Postdoctoral Research Associate (Formerly), Department of Civil and Environmental Engineering, University of Connecticut, 261 Glenbrook Road, Unit 3037, Storrs, CT 06269-3037, [2]Professor, Department of Civil and Environmental Engineering, University of Connecticut, 261 Glenbrook Road, Unit 3037, Storrs, CT 06269-3037. (Contact: ramesh.malla@uconn.edu)

Introduction: Extreme environmental hazards (e.g., ionizing radiation, large temperature variations, and meteoroid impacts) must be considered in the design of future lunar habitats. Previous studies [1], [2] suggests that a properly designed protective regolith / soil cover may protect against these hazards. In this work, methodologies for modeling hypervelocity impact (HVI) cratering in lunar base structures are discussed, based on spacecraft design criteria and planetary impact cratering research [3]-[6].

Methods: Unshielded (aluminum alloy) and shielded (dry sand) targets are considered. In view of the low cohesive strength of lunar regolith, cohesionless dry sand is used as a model to approximate the behavior of regolith for shielded targets. Empirical equations (thick-target versions of the Fish-Summers and modified Cour-Palais penetration equations) [3], [4] and scaling laws (nondimensional Holsapple and Schmidt-Housen laws for cratering in cohesionless targets) [5], [6] are used to compute the sizes of craters produced by meteoroid impacts on aluminum alloy and dry sand targets. The empirical equations express crater depth for a semi-infinite (thick) unshielded target (h_∞) as a function of projectile and impact characteristics [e.g., projectile mass (m_p) and density (ρ_p), impact velocity component normal to the target surface (V_n), etc.] as well as target material properties; for instance, the thick-target version of the Fish-Summers penetration equation expresses h_∞ as follows:

$$h_\infty = K_\infty m_p^{0.352} \rho_p^{1/6} V_n^{2/3} \qquad (1)$$

Here, K_∞ is a constant that characterizes the target material. The thick-target version of the modified Cour-Palais equation similarly expresses crater depth as a function of projectile and impact characteristics, but also takes into account the hardness of the target material. On the other hand, the Holsapple and Schmidt-Housen scaling laws for shielded targets (i.e., cohesionless dry sand layers) are nondimensional power laws that express the crater volume [in the form of the nondimensional "cratering efficiency" (π_∇)] as a function of projectile and impact characteristics [in the form of the nondimensional "gravity-scaled size" (π_g)]:

$$\pi_\nabla = K \pi_g^{-\theta} \qquad (2)$$

Here, K and θ are constants that characterize the target material (i.e., dry sand). The cratering efficiency (π_∇) is the ratio of the crater material mass to the projectile mass, while the gravity-scaled size (π_g) can be interpreted as the ratio of the lithostatic pressure to the dynamic pressure. Computational parametric analyses are conducted to estimate crater characteristics in HVI scenarios covering a wide range of impact velocities and projectile properties (i.e., projectile materials, masses, and mass densities), as well as several target materials (aluminum alloys and dry sand layers). All computations are performed using in-house programs developed and verified in the MATLAB scientific computing environment.

Results: Similarities and differences in the predictions of the Fish-Summers and modified Cour-Palais empirical equations for HVI cratering in aluminum alloy targets are discussed. The predictions of the Holsapple and Schmidt-Housen scaling laws are similarly discussed. It is observed that the thick-target version of the Fish-Summers equation is more conservative than the modified Cour-Palais equation from a design standpoint, while the Holsapple and Schmidt-Housen scaling laws are essentially equivalent. Physical implications of the results are interpreted and discussed from a structural design perspective, and the crater size estimates in dry sand targets computed using the scaling laws are compared with those obtained from a web-based crater size estimation resource [7].

References:

[1] Jablonski A. M. and Ogden K. A. (2008) *J. Aerosp. Eng., 21,* 72-90. [2] Benaroya H. and Bernold L. (2008) *Acta Astronaut.*, *62,* 277-299. [3] Lambert M. (1997) *Adv. Space Res.*, *19,* 369-378. [4] Christiansen E. L. (1993) *Int. J. Impact Eng.*, *14,* 145-156. [5] Holsapple K. A. (1993) *Annu. Rev. Earth Planet. Sci.*, *21,* 333-373. [6] Schmidt R. M. and Housen. K. R. (1987) *Int. J. Impact Eng.*, *5,* 543-560. [7] Holsapple, K., v.1.4 10/07, Lunar and Planetary Institute. (n.d.) Accessed November 17, 2022. https://www.lpi.usra.edu/lunar/tools/lunarcrater-calc/

BuzzCraft: Alternative Fully Resusable Concept Architectures for Lunar GATEWAY & ARTEMIS.

B. Manucha[1] and M. Thangavelu[2], [1]University of Southern California, manucha@usc.edu, [2]University of Southern California, mthangav@usc.edu.

Introduction: As part of the Artemis program, NASA intends to have boots back on the moon by 2024, with help from the Gateway station in Lunar orbit. However, questions persist about the physiological consequences of prolonged exposure to deep space radiation on the crew, especially during the upcoming sunspot cycle 25 solar maximum period that will peak during Artemis mission execution. Furthermore, there is currently no cislunar infrastructure in place to aid with rescue missions in the event of an anomaly requiring crew extraction on the lunar surface, nor is there a reliable logistics channel and communications link to the Moon.

BuzzCraft concept architecture is an alternative to the current Gateway station proposal that seeks to address both of these issues. BuzzCraft architecture will evolve over the course of four quick stages in rapid cadence between 2022 and 2024 and intends to put a woman and a man on the Moon by the end of 2024. The first stage is a SpaceX Dragon and NASA Orion module docked together in Low Earth orbit containing a Plant and Animal laboratory (PAL). PAL's initial phase in LEO within Earth's magnetosphere will serve as a control for study of biological tissue taken from plants and animals in the capsule. At this stage the teleorobotic systems needed for PAL operations and maintenance between crew assisted rack and sample changeouts are tested and certified. After this initial phase, PAL will move into phase 2: Geostationary orbit where it will be beyond the protection of Earth's magnetosphere and the biological tissue will be exposed to deep space radiation for prolonged periods of time. PAL will be relatively quickly accessible by crew in short visits to GSO for rack changeouts and collecting tissue samples. Phase 3: PAL will move back into LEO where other modules and fully reusable propulsion systems will be clustered with help from international partners. The successful demonstration of the Low Earth Orbit Flight Test Inflatable Decelerator(LOFTID) shows promise for returning propulsion systems for refurbishment and reuse. After the modular assembly of the constituent modules and propulsion are stacked, Buzzcraft will be injected into a free-return cislunar orbit. PAL will be attached to Buzzcraft to continue the biological studies, and other modules will carry cargo, landers, and crew into cislunar orbit. Once in this orbit, Buzzcraft will be a critical piece of cislunar infrastructure and will aid the Artemis mission in carrying payloads to the moon. This Buzzcraft cislunar Cycler would serve as a crew emergency and rescue system and also initiate the evolution of a cislunar logistics channel adding vital value to the Artemis effort. Eventually, Buzzcraft could also evolve into Gateway in different orbits including the near rectilinear halo lunar polar orbit(HALO) that is proposed currently.

The architecture of BuzzCraft is composed of already existing commercial space technology, both human rated and non-human rated, including SpaceX's Dragon capsule, the Falcon 9 and Falcon Heavy launchers, as well as Boeing's *Unity* connection module. Tried and tested Apollo hardware including the Lunar Module(LM) and he Apollo lunar surface EVA suit can be quickly upgraded for the Artemis III mission. As a result, the first phase of BuzzCraft could be launched as soon as 2022. Operations in low Earth orbit enable both commercial and international partners to engage in quickly evolving Buzzcraft cislunar architecture. Furthermore, modules and payloads can be supplied by international partners such as the ESA, RosCosmos, CNSA, JAXA, and ISRO as well as emerging nations with space faring ambitions.

References: [1] NATIONAL SPACE POLICY UNITED STATES OF AMERICA https://trumpwhitehouse.archives.gov/wp-content/uploads/2020/12/National-Space-Policy.pdf [2] Smith, M., Craig, D., Herrmann, N., Mahoney, E., Krezel, J., McIntyre, N., & Goodliff, K. (2020, March). The artemis program: An overview of nasa's activities to return humans to the moon. In 2020 IEEE Aerospace Conference (pp. 1-10). IEEE. [3] SpaceX Falcon 9 https://www.spacex.com/vehicles/falcon-9/ [4] SpaceX Falcon Heavy https://www.spacex.com/vehicles/falcon-heavy/ [5] SpaceX Dragon SpaceX - Dragon [6] NASA Crew Dragon Crew Dragon | NASA [7] Boroson, D. M., Scozzafava, J. J., Murphy, D. V., Robinson, B. S., & Lincoln, M. I. T. (2009, July). The lunar laser communications demonstration (LLCD). In 2009 Third IEEE International Conference on Space Mission Challenges for Information Technology (pp. 23-28). IEEE. [8] Laser Communications Relay Demonstration Lifts Off!(2021) Laser Communications Relay Demonstration Lifts Off! | NASA [9] Edwards, B. L., Israel, D. J., & Vithlani, S. K. (2018, February). Latest changes to NASA's laser communications relay demonstration project. In Free-Space Laser Communication and Atmospheric Propagation XXX (Vol. 10524, p. 105240P). International Society for Optics and Photonics. [10] Robinson, B. S., Shih, T., Khatri, F. I., Boroson, D. M., Burnside, J. W., Guldner, O., ... & Seas, A. (2018, February). Laser communications for human space exploration in cislunar space: ILLUMA-T and O2O. In Free-Space Laser Communication and Atmospheric Propagation XXX (Vol. 10524, p. 105240S). International Society for Optics and Photonics. [11] Whitley, R. J., Davis, D. C., Burke, L. M., McCarthy, B. P., Power, R. J., McGuire, M. L., & Howell, K. C. (2018, August). Earth-moon near rectilinear halo and butterfly orbits for lunar surface exploration. In AAS/AIAA Astrodynamics Specialists Conference, Snowbird, Utah. [12] Dempsey, M. A. (2021). ARCHER: A Reimagined Cycler for Human ExcuRsions. In *AIAA Propulsion and Energy 2021 Forum* (p. 3259). [13] Lali, M., & Thangavelu, M. (2016). MOBIUS: An Evolutionary Strategy for Lunar Tourism. In AIAA SPACE 2016 (p. 5389). [14] Aldrin, B., Byrnes, D., Jones, R., Davis, H., & Thangavelu, M. (2001). Evolutionary space transportation plan for Mars cycling concepts (pp. 28-30). AIAA. [15] Roukos, D., & Thangavelu, M. (2010, August). Construction of an International Space Transit Vehicle Using the Space Station. In AIAA SPACE 2010 Conference & Exposition (p. 8876). [17] Thangavelu, M. (1991). MALEO: modular Assembly in low earth orbit: alternate Strategy for lunar base development. Journal of Aerospace Engineering, 4(3), 256-273. [18] Thangavelu, M., & Dorrington, G. E. (1988). MALEO- Strategy for lunar base build-up. In IAF, International Astronautical Congress, 39 th, Bangalore, India (p. 1988). [19] Schrunk, D., Sharpe, B., Cooper, B. L., & Thangavelu, M. (2007). The moon: Resources, future development and settlement. Springer Science & Business Media. [20] Genova, A. L., & Aldrin, B. (2015, August). Circumlunar Free-Return Cycler Orbits for a Manned Earth-Moon Space Station. In Proceedings of the AAS/AIAA Astrodynamics Specialist Conference, Vail, CO. [21] Thangavelu, M. (2020). USC ARTEMIS Project: Maximum Impact Moon Mission (MAXIM) Tribute to Apollo. In ASCEND 2020 (p. 4098). [22] Mann, S. C., Bowes, A., Deshmukh, R. G., & Dutta, S. (2022). Small Satellite-Sized Hypersonic Inflatable Aerodynamic Decelerators for Interplanetary Science Missions. [23] Swanson, G. T., Kazemba, C. D., Hughes, S. J., Johnson, R. K., Lindell, M. C., Bodkin, R. J., ... & Cheatwood, F. M. (2019, July). Loftid Aeroshell Engineering Development Unit Structural Testing. In International Planetary Probe Workshop (No. ARC-E-DAA-TN66439). [24] Hughes, S., Cheatwood, F., Dillman, R., Calomino, A., Wright, H., DelCorso, J., & Calomino, A. (2011, May). Hypersonic inflatable aerodynamic decelerator (HIAD) technology development overview. In *21st AIAA Aerodynamic Decelerator Systems Technology Conference and Seminar* (p. 2524). [25] Low-Earth Orbit Flight Test of an Inflatable Decelerator Low-Earth Orbit Flight Test of an Inflatable Decelerator - Wikipedia

Tall Lunar Tower: An Autonomously Assembled Tower for Early Lunar Infrastructure.

J. R. Martin[1] and M. K. Mahlin[1], [1]NASA Langley Research Center, 8 W Taylor St, MS 190, Hampton, VA 23681. (Contact: jacob.martin@nasa.gov)

Introduction: Towers provide a mass-efficient method to elevate payloads above a planetary surface. At the lunar south pole, solar modules at high elevations will allow for more accessible and sustained power generation. To implement towers that support power generating payloads greater than 50 kW, in-situ assembly presents a more mass- and volume-efficient solution than traditional deployable methods [1]. The Tall Lunar Tower (TLT) project aims to enable a new class of solar power supply at the lunar south pole by ground demonstrating autonomous robotic assembly of a 50-meter tower.

TLT Overview: The TLT team is designing an engineering development unit (EDU) for the autonomous construction of a 50 m tower. Solar arrays are a payload type of primary interest for tall towers. A 50 m TLT would reduce the duration of lunar night from 14 Earth days to two, as shown in Fig. 1. The autonomous assembly of a tower also demonstrates a cross-cutting assembly technology that can be applied to other structures, including blast shields, radiation shelters, and safe havens. The team has developed a tower sizing utility to quickly evaluate tower configurations of different materials, strut types, and payload sizes. Tower configurations were evaluated with detailed models under structural and thermal load conditions expected at the lunar south pole [2]. The TLT team is considering a square-bay truss with a payload capacity of 1500 kg on the lunar surface. Currently, the project is preparing for an August 2023 EDU demonstration after recently passing a Preliminary Design Review.

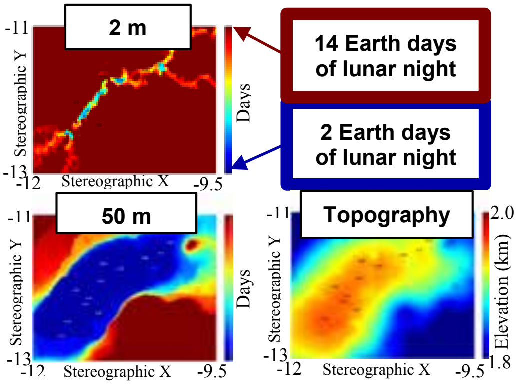


Fig. 1: Elevation vs Duration of Lunar Night

Robotic Assembly: A primary focus of the TLT project is the robotic assembly approach for a truss structure. Major robotic components of the TLT system including manipulators, a jig, and a tower lifter are shown in Fig. 2. The team is using generic commercial off-the-shelf (COTS) manipulators with custom end effectors to place truss components in a robotic jig. The end effectors are designed to assemble the truss with one-sided blind fasteners, such as rivets, which provides flexibility for future fastening methods. The lifter is a component of the jig that translates the assembled truss bays upward. The lifter is sized to elevate a tower with a pre-integrated payload in lunar gravity.

The COTS manipulators allow for software development to be modular and support future space-rated manipulators. The assembly will use stereovision cameras to provide fine alignment of the truss joints and ensure assembly accuracy. Each assembled bay will be measured by the depth cameras and load tested by the lifter prior to assembling the following bay.

Initially, a flight version TLT will be built on a lunar lander deck. However, future versions would be transportable to prepared foundations. The assembly robotics will also be reusable and the tower will scale with the quantity of parts provided.

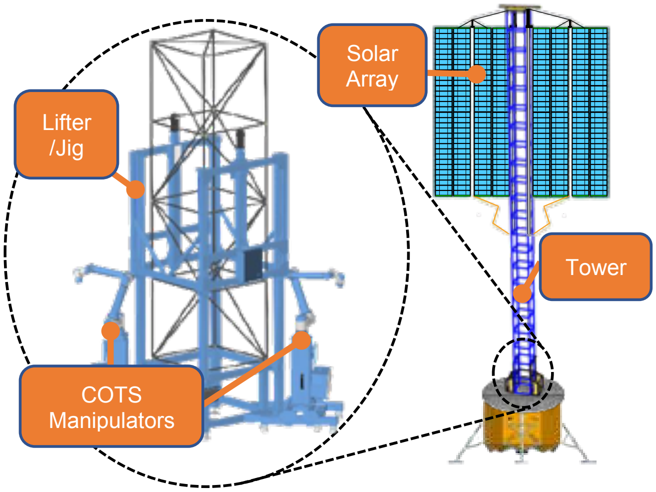


Fig. 2: Robotic Assembly System for TLT EDU

References: [1] Doggett W. R., et al. (2023) *AIAA SciTech 2023 Forum, 10.2514/6.2023-0383.* [2] Song K. et al. (2023) *AIAA SciTech 2023 Forum, 10.2514/6.2023-0382.*

Robotic Manipulators for Thermal Reconfiguration of Spacecraft.

G. D. Mavor[1], S. P. Dougherty[1] and Z. T. Nishino[1], Maxar, 1300 W. 120th Ave, Westminster, CO 80234. (Gregory.Mavor@Maxar.com)

Introduction:

The extreme environments of the Lunar surface pose a serious challenge to sustained presence on the moon. Vehicles and equipment designed to operate on the lunar surface need to incorporate thermal management techniques to keep core systems operational throughout extended periods of both extreme hot and extreme cold. Moreover, many of the key areas in lunar exploration require a robotic manipulator to move materials, parts, objects or tools whose use-case could be extended to include robotic reconfiguration of a spacecraft for thermal management purposes. Conventional heaters and multi-layer insulation (MLI) blanketing provide a well understood, low risk method of keeping critical robotic systems within their operational temperature limits in the lunar environment, and have been demonstrated to perform amply on robotic systems such as the Sample Acquisition Morphology, Filtering and Probing of Lunar Regolith (SAMPLR) mission. Using a robotic manipulator for reconfiguration of a spacecraft for thermal purposes allows for simpler spacecraft-level thermal management systems (TMS) and reduced spacecraft mass achieved via reuse of the manipulator TMS.

Robotic Manipulator Thermal Management:

A conventional robotic manipulator's TMS eliminates the need for costly cryogenic components while simultaneously enhancing system joint torque density, time-to-launch, and cost-effectiveness. For example, on the SAMPLR mission, actuator heating uses as little as 10 W average while adding only ~350 g of additional mass to a 1.3 m long 5-DOF manipulator [1]. This is possible because the MLI blankets shown in Figure 1 are very insulative in the vacuous lunar environment with a typical heat leak in vacuum of approximately 5.3 W/m² [2], while normal system operations create self-heating of their own. Minimally heating a manipulator for survival in the lunar environment can therefore leverage existing energy storage and power systems already required with little impact to the spacecraft design.

Figure 1: Blanketed SAMPLR Robotic Manipulator

Robotic Reconfiguration of Spacecraft for Thermal Management:

Thermal reconfiguration of a spacecraft via the use of a robotic manipulator allows for a simpler traditional spacecraft-level TMS and reduces overall mass and power consumption while leaving valuable deck space available for payloads. Robotically reconfiguring or relocating covers to increase insulation or radiation around the spacecraft eliminates the need for numerous dedicated actuators while also enabling payload specific thermal conditions. Figure 2 shows estimated power consumption of an Apollo Lunar Roving Vehicle (LRV) over the course of a 354 hr eclipse event where the spacecraft is manually reconfigured for thermal survival. 66 W of total power is required for vehicle survival throughout the eclipse event.

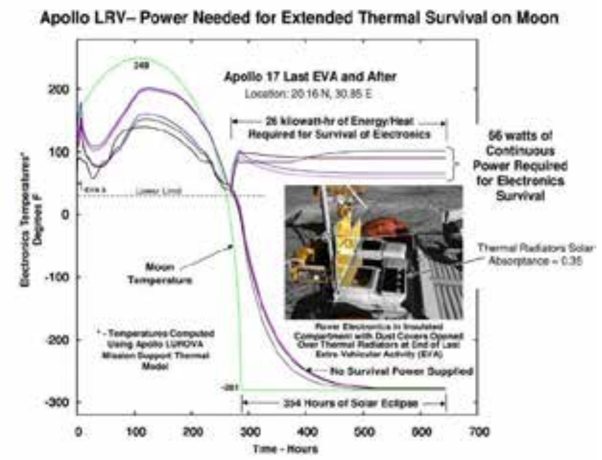


Figure 2: Apollo LRV TMS Power Consumption [3]

Using a SAMPLR-like robotic manipulator with a conventional TMS for thermal reconfiguration of a lunar vehicle reduces the power consumption of heaters at the spacecraft level and, in turn, decreases required battery capacity.

References:

[1] M. A. Seibert et al. (2020) *51st Lunar and Planetary Science Conference,* Sample Acquisition Morphology, Filtering and Probing of Lunar Regolith (SAMPLR) Payload. [2] T. Miyakita et al. (2015) *45th International Conference on Environmental Systems,* Evaluation of Thermal Insulation Performance of a New Multi-Layer Insulation with Non-Interlayer-Contact Spacer. [3] R. A. Creel. (1995) *Apollo Lunar Surface Journal.* Apollo Rover Lessons Learned.

Regolith-Derived Extensible Feedstocks for the Manufacture of Chemical Precursors and Materials.

M.A. Miller, Southwest Research Institute, 6220 Culebra Road, San Antonio, TX 78238. (mmiller@swri.org)

Introduction: The volatiles on the Moon are far more abundant than even optimistic estimates had predicted prior to numerous discoveries made in 2009 [1], [2], [3], [4] . This inventory includes not only water ice (5.5%), but also other, often ignored constituents of lower abundancies, such as hydrogen sulfide (0.92%), ammonia (0.33%), carbon monoxide (0.57%), and ethylene (0.17%). In-situ resource utilization (ISRU) of such species, when combined with the regolith itself and lunar-based processes for synthesis of extensible chemical intermediates, offers exciting possibilities that enable the manufacture of important chemical precursors and materials on the lunar surface and within the cislunar space, including structural materials and propellants. Orbital manufacturing has the potential to enable substantial returns for the science and space technology communities by providing the ability to assemble larger apertures and solar arrays than feasible on Earth-assembled satellites to achieve greater spatial resolution and light collection for powering instruments. Integration of ISRU capabilities into lunar mission architectures and plans can greatly reduce the launch mass, costs, and associated risks.

Objectives: Our work seeks to derive silazane-type ($H_2Si\text{-}NH\text{-}$) chemical intermediates and oligomers, as well as polymers derived from a crucial metastable molecule, carbon suboxide (C_3O_2), from the lunar regolith using foundational materials synthesis and process engineering. These extensible feedstocks may be used to manufacture different materials with targeted properties for different applications, including rigid structures to support large facilities on the lunar surface or orbital manufacturing of large aperture instruments, functional materials for advanced large-area photovoltaic arrays, and propellants. Each product is based on a common class of molecular building blocks. Accordingly, “extensible” in the present context characterizes a materials manufacturing paradigm allowing multiple capabilities and functionality from a common feedstock that is derived from the lunar regolith and utilized for surface and orbital manufacturing.

Plasma-Assisted Synthesis: The objectives are centered on a novel approach for synthesizing polysilazane and prosiloxane intermediates (and oligomers thereof) from volatiles of the regolith and the regolith itself that can be converted to silicon nitride (Si_3N_4) via subsequent thermal processing [5]. Silicon nitride is an important material for structural, electronic, and photovoltaic applications.

Using magnetic induction processing, the ability to derive silane (SiH_4) directly from the plagioclase, olivine, and pyroxene mineral phases of the regolith provides a valuable precursor for plasma synthesis of polysilazanes $[H_2Si\text{-}NH]_n$ by utilizing available stores of ammonia as the co-reactant [6]. In this reaction pathway, silicate and magnesium bearing mineral phases are converted directly to magnesium silicide (Mg_2Si), an important intermediate readily converted to silane (as well as disilane and H_2) in the presence of ammonia and under non-equilibrium plasma conditions (Fig. 1).

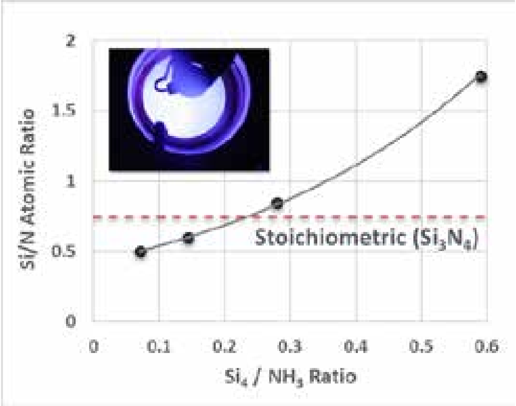


Fig. 1. Plasma products vs. silane/ammonia ratio generated in a non-thermal plasma reactor.

Starting from carbon monoxide as a simple feedstock, we have further demonstrated the use of non-thermal reactive plasmas to synthesize poly(carbon suboxide) – a substantially amorphous polymeric material having useful energetic properties for the basis of solid propellants [5]. The specific impulse (Isp) of propellant formulations that incorporated this ingredient was 382 s, exceeding the Isp of conventional double-base propellants.

References: [1] Gibson Jr, E. and Johnson, S.M. (1971) *LPSC Proceedings.*[2] Abell, P.I. et al. (1970) *Science, 167:* 757. [3] Abell, P.I. et al. (1970) *Nature, 226:* 251-252. [4] Pieters, C.M. et al. (2009) *Science 326:* 568. [5] Miller, M.A. (2022) *NSMMS & CRASTE Joint Symposia*, Madison, WI. [6] Anderson, H.M. et al. (1935) *J. Appl. Phys.67(9):* 3999-4011.

Metal-coated Halloysite Nanotube Based Antimicrobial Filtration System for Space Mission Applications. M. J. P. Bappy[1] and D. K. Mills[2], [1 2]Louisiana Tech University, 201 Mayfield Ave, Ruston, LA 71272, USA. (Contact: dkmills@latech.edu)

Introduction: Space flight induces a reduced immune competence among crew because of the long journey, difficulty of maintaining a healthy microbiome, change in diet, etc., leading to an increased risk of bacterial and viral infections. A healthy human-crewed space mission requires antibacterial protection against airborne pathogens by acting to deactivate a virus, reduce or eliminate bacterial adhesion, and prevent bacterial growth [1]. Furthermore, removing particulate materials, particularly silicon, titanium dioxide, and other harmful materials, is critical.

Metallic nanomaterials can address the many challenges regarding lunar and planetary dust and other potentially dangerous particulate materials [2]. Our proposal targets the development of filter and filtrations systems for astronaut spacesuits, NASA Crewed Space Missions, NASA Mars and Lunar habitats, and NASA installations. We have developed a metalized nanofiber-based and 3D-printed air filtration unit and systems. Our filtration unit protects against the entry of pathogens and particulate material (dust/DNA/particulates). The porosity of our filter membrane (50 nanometers) prevents the entry of pathogens and uses embedded metal ions to enhance entrapment, containment, purging, and analysis of entrapped material.

Methods: Metal-coated (Ag, Cu, and Zn) halloysite nanotubes (mHNTs) were developed to produce air-tight and interchangeable filters and filter housings (figure 1). We developed a method for metalizing (copper, gold, magnesium, silver, zinc) the surface of a natural clay-like material, halloysite nanotubes (HNTs). These metalized HNTs (mHNTs) were used to create a 3D printer antimicrobial filament, blow-spun mHNT fibers and films, and surface coatings. Our method offers a one-step and low-cost process with many other advantages. With solution blow spinning, the deposition of mHNTs or dual-coated mHNTs can be sprayed on a 3D printed framework as a fibrous membrane or film coating. Filters can also be coated with various substances that mitigate the entry of nano- and microparticles smaller than 50 nanometers. In vitro antibacterial/ inti-viral tests and bacterial growth inhibition studies were done to validate the pathogen protection capability of the fibers. Further experimentation and testing using the facilities of the Aerosol Impacts & Research (AIR) Lab is needed to validate the performance of our filtration system. This technology can enhance life support systems in crewed spacecraft and habitats and provide containment against Martian biological and particulate entry.

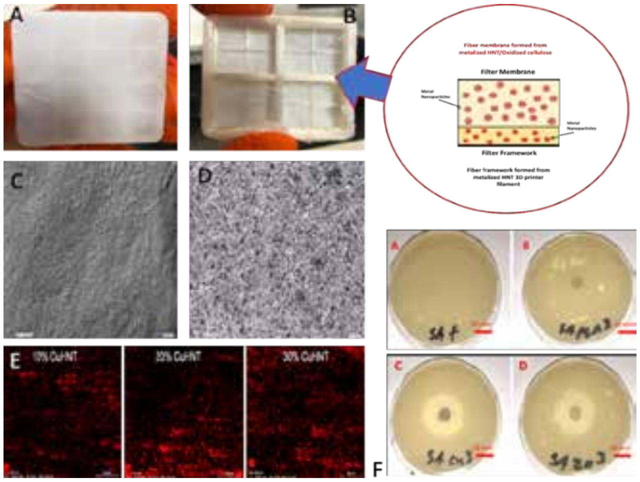


Figure 1. Filter System. (A and B) Frame housing. (C) Digital micrograph (D) Higher power digital micrograph (E) EDS picture of copper coated HNTs (F) Cultures of *S. aureus.*

References:

[1] Taylor P. W. (2015) *Infect. Drug Resist.*, 249–262. [2] McFarland A. W. et al. (2022) *Polymers, 14,* 8.

In-Situ Artificial Substrate Witness Plates: A Passive Tool to Assess Materials for Long-term Exposure

L. Morrissey[1,2], P. Saxena[2], J. McClain[2], N. Curran[2], and R. M. Killen[2], [1]Memorial University, NL, Canada, Washington, DC 20005, USA, [2]NASA GSFC, Greenbelt, Maryland 20771, USA

Introduction: Given the stark increase in lunar orbital and surface efforts by several countries, there is a pressing need to better understand several scientific and operational relevant surface processes. A NASA led effort to return astronauts to the Moon, Artemis, is an initial step to long-term sustainable human presence at the Moon. However, key Lunar processes relevant to material performance are known to vary spatially and temporally [1]. Thus, the goal of establishing a sustained presence on the Moon relies on understanding how such processes can modify exposed operationally significant materials. In particular, the solar wind (SW) is a stream of high-energy charged particles originating from the sun consisting of electrons, protons, and trace amounts of heavy ions. Because the Moon does not possess an atmosphere or intrinsic magnetic field to shield it from the SW; its surface is constantly impacted. As SW ions impact the surface, they deposit energy, leading to the emission of surface atoms, erosion, and damage [2]. Understanding the effects of SW impacts on materials placed on the lunar surface is therefore critical to designing long-term lunar structures.

Artificial Witness Plates for the Future: In this study, we discuss the potential value of a tool complementary to these techniques: in-situ artificial substrate witness plates (termed ‘Biscuits’) for material assessment. Witness plates can potentially simultaneously assess the performance of several different materials as a function of time and location. These plates are low cost, low mass, and produce a low environmental footprint. Exposed plates would be fully characterized pre and post exposure, allowing for comparison of identical structures.

To demonstrate the unique ability of biscuits to capture valuable solar activity related effects we have conducted a case study using the binary collision approximation (BCA) simulation tool, SDTrimSP. For this case study we simulate SW impacts onto a pure aluminum target, a commonly used operational material that could be exposed on the Lunar surface for extended durations. Following recommended best practices, we approximate the SW as 96% 1 keV H^+ and 4% 4 keV He^{++} impacting an aluminum target with an energy of 1 keV/amu. Using a SW flux of $4x10^8$ cm^2/s, a total fluence corresponding to 10 Earth years of dynamic SW exposure was simulated. The average aluminum sputtering yield was ~ $5x10^{-2}$ Al atoms/ impact. Extending this over 10 earth years, this corresponds to ~$6.3x10^{15}$ Al atoms/cm^2. For a 20 cm^2 biscuit this would correspond to a total mass loss of 0.056 mg and 0.11 mg for 5- and 10-years exposure respectively. This total mass loss from the biscuit is well above detection limits for changes in total mass and demonstrates the applicability for biscuits to be used to quantify SW processes while also assessing the performance of different operational materials. In addition, SDTrimSP can be used to study the depth and damage produced during exposure. After 10 years of exposure to the SW significant damage has accumulated in the sample due to incident SW. As incoming energetic SW ions make their way through the target they deposit energy along the way, eventually reaching a ‘final’ depth. Therefore, the depth of SW induced damage, peaks at 150 A within the sample, shallower than the peak in number of implantations, 50 A. As such, thin biscuit samples can capture the entire deposition and damage profile during exposure.

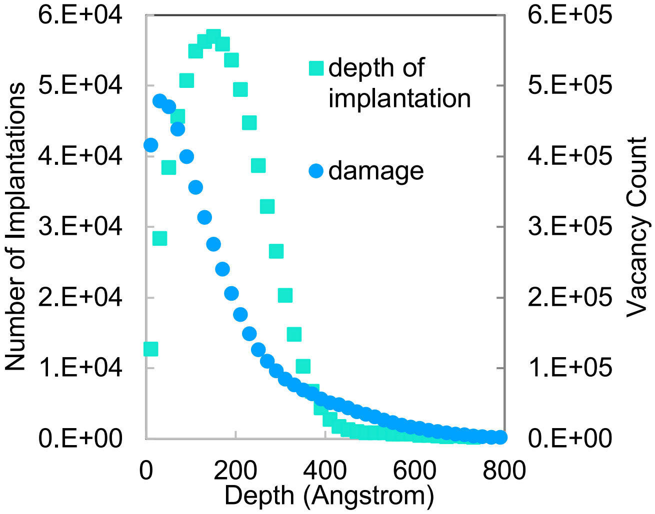


Fig. 1 SW implantations and damage as a function of target depth

References: [1] W. M. Farrell et al. (2017) JGR. [2] R. Behrisch and W. Eckstein (2007)

Chemically modified reduced graphene oxide (CMrGO) in Electrodynamic Dust Shield (EDS) applications.

M. J. Schaible[1], K. G. Sjolund[1], E. A. Ryan[1], M. L. Shofner[1], J. S. Linsey[1], John R. Reynolds[1], and T. M. Orlando[1], [1]Georgia Institute of Technology, 901 Atlantic Dr. NW, Atlanta GA 30318. (Contact: mjschaible@gatech.edu)

Introduction: The return of manned missions to the moon requires novel solutions to the unique problems posed by lunar dust. One relatively mature technology is Electrodynamic Dust Shielding (EDS) [1,2]. EDS is an active dust mitigation technique which uses alternating electric fields applied to interdigitated electrodes to move dust through dielectrophoretic and Coulombic repulsive forces. For EDS systems to operate on the lunar surface, it is important that they can be (i) run at relatively low applied potentials (<1 kV), (ii) quickly and easily manufactured and repaired in situ, and (iii) easily combined with additional dust mitigation solutions (e.g., electron bombardment or nanostructured coatings). This report will describe recent work investigating novel EDS materials for planar (2D) EDS, and the effects of surface coatings, UV, and electron bombardment on the effectiveness of EDS.

Chemically modified reduced graphene oxide (CMrGO) EDS systems: Planar EDS systems were prepared using a recently developed conducting polymer nanocomposite containing chemically modified reduced graphene oxide (CMrGO) [3,4]. The EDS devices were prepared by spray-coating a high density polyethylene substrate through a patterned mask followed by a melt-press lamination (shown in Figure 1). This process produces a surface-localized, electrically conductive nanocomposite which serves as the electrode material for the EDS applications described here.

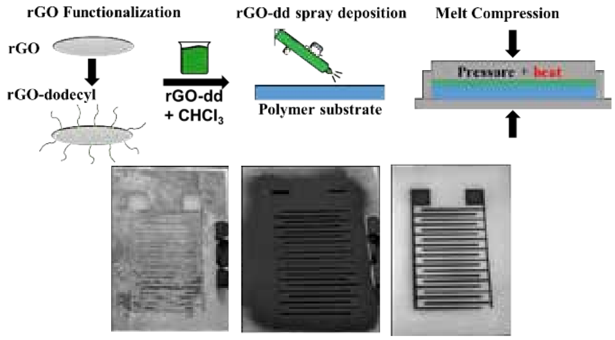


Figure 2: (A) Reduced graphene oxide chemically modified with dodecyl substituents (CMrGO) was dispersed in CHCl$_3$ and (B) sprayed over a removable steel mask. (C,D) Sprayed substrates were then subject to heat and pressure to create an infiltrated surface-localize nanocomposite device. (E) Masked substrate before spraying (left), masked substrate sprayed with CMrGO (middle), patterned EDS devices (right).

CMrGO EDS Dust Mitigation Testing: The EDS performance was tested for a dusting of lunar regolith simulant under high vacuum conditions (~10^{-6} Torr) using both 2-phase and 3-phase device configurations. Uncapped (bare) devices showed efficient dust removal at moderate voltages (1000 to 3000 V) for both 2-phase and 3-phase designs. Further tests carried out while illuminating the dust surface with a UV excimer lamp or vibrating the surface to cause grain tribocharging reduced the EDS voltage needed to reach the maximum cleanliness by almost 50% for the 2-phase devices (500 V minimum for rough and 1000 V for smooth). Interestingly, the 3-phase devices were unaffected by the application of UV. Capping the CMrGO traces with low density polyethylene eliminated breakdown of the materials and device degradation, but larger voltages (3000 V) coupled with UV illumination were required to remove the grains from the capped devices. Additional nanostructured coatings are currently being tested with the CMrGO substrates to determine if they improve the EDS efficiency, particularly in the removal of the smallest dust grains.

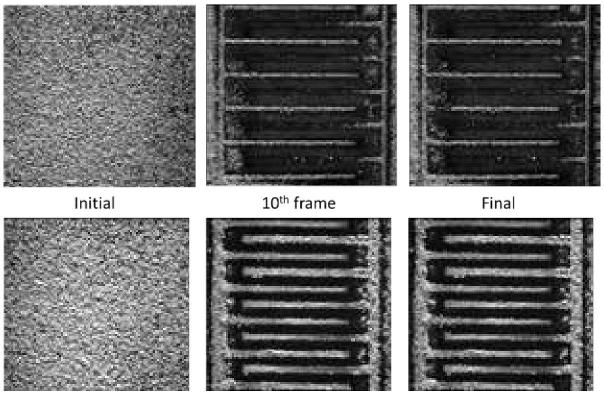


Figure 1: Surface cleanliness vs. time for (top) 'rough' and (bottom) LDPE-capped CM-rGO EDS devices using 500V and 3000V, respectively.

This work was directly supported by the NASA Solar System Exploration Research Virtual Institute (SSERVI) under Cooperative Agreement #NNA17BF68A (REVEALS).

References: [1] Johansen M. R. et al. (2015) *AIAA*, 2015-4446. [2] Calle C. I. et al. (2006) *NTRS,* KSC-2006-125. [3] Seibers Z. D. et al. (2020) *ACS* 1145-11464. [4] Seibers Z. D. et al. (2019) *PE&S,* Vol. 60 Iss. 1, p86-95

Lunar In-Situ Aluminum Production via Molten Salt Electrolysis (LISAP-MSE).

J. N. Ortega[1], J. Smith[1], F. Rezaei[1], D. Bayless[1], W. Schonberg[1], D. Stutts[1], and D. Han[1], [1]Missouri University of Science and Technology, 1870 Miner Circle, Rolla, MO 65409. (Contact: handao@mst.edu)

Introduction: The goal of Artemis is to establish a sustained presence on the Moon. To achieve so, numerous resources are necessary. The Moon contains several essential elements needed to sustain human presence. Most of those elements are trapped in the form of minerals [1]. To refine those minerals into useful materials, reduction methods are needed.

Most reduction methods on Earth require large amounts of mass and power which is unrealistic for early stages of building a lunar base. To solve this problem, we developed a process for Lunar In-Situ Aluminum Production via Molten Salt Electrolysis (LISAP-MSE).

The LISAP-MSE project, if successful, will demonstrate the use of the Fray-Farthing-Chen (FFC) Cambridge process 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 1 below.

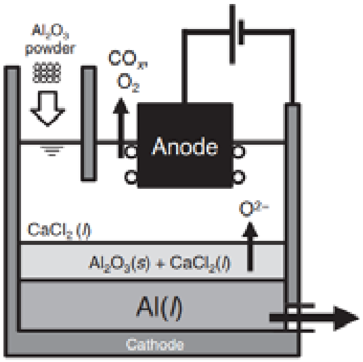


Figure 1: Aluminum Oxide Electrolysis [2]

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 the FFC Cambridge process (except hydrogen chloride) to produce aluminum metal, oxygen, water, and silica from anorthite. Once sourced and constructed, the LISAP-MSE apparatus will be characterized and calibrated in an atmospheric pressure setting before being tested inside vacuum chambers. These testing conditions include under atmospheric pressure and under vacuum conditions.

Once testing is completed, the end product will be characterized using a handheld X-ray fluorescence (XRF) analyzer along with density tests to verify the elemental composition. Following the XRF analysis is a set of density tests that will be compared to the densities of pure aluminum and pure alumina. This will help determine the amount of aluminum produced, and thus assess the efficiency of conversion.

Assuming a maximum yield of 100%, 27 g of aluminum metal, 45 g of water, and 11 g of oxygen gas can be yielded from 182 g of hydrochloric acid as shown in Table 1 below,

Table 1: Stoichiometric Yields

Name	Formula	Net Consumption		Net Yield	
		(mole)	(g)	(mole)	(g)
Hydrogen Chloride	HCl	5	182	-	-
Water	H_2O	-	-	2.5	45
Anorthite	$CaAl_2Si_2O_8$	1	278	-	-
Silica	SiO_2	-	-	2	120
Calcium Chloride	$CaCl_2$	-	-	1	111
Aluminum Metal	Al	-	-	1	27
Oxygen Gas	O_2	-	-	1	11

Based on our study of existing literature, we assess the entry TRL of the proposed LISAP-MSE concept at 2-3 (analytical and experimental critical function and/or characteristic proof of concept). Through this project, we aim to elevate the TRL to 4-5 (component and/or breadboard validation in relevant environment) and pave the way for large scale aluminum production on the Moon [3]. Mainly driven by chemical reactions, the LISAP-MSE process is massively scalable allowing for a smooth transition from testing phase to batch production. This aluminum can be used to construct habitats and infrastructure for a lunar base which can potentially support a sustained human presence on the Moon.

References: [1] Heiken G. H. et al. (1991) *Lunar SourceBook,* 121-150. [2] Kadowaki H. et al. (2018) *Journal of The Electrochemical Society,* 165. [3] NASA (2012) *Technology Readiness Level.*

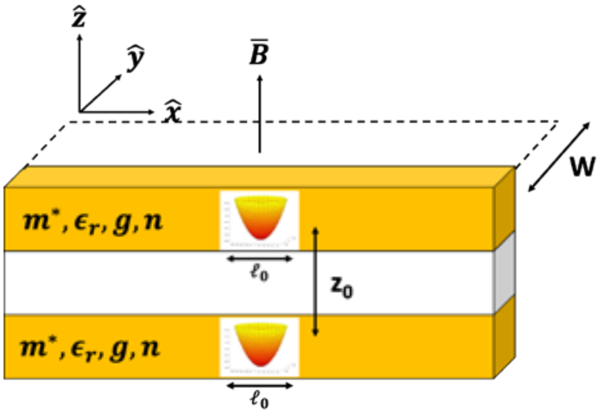
Lunar Temperature Effects on Spin Qubit Generation.

G. Panda[1], N. Sebasco[1], J. Vetere[1], V.M. Ayres[1] and H.C. Shaw[2], [1] Department of Electrical & Computer Engineering, Michigan State University, East Lansing, MI 48824 USA, [2]Code 5560, NASA Goddard Space Flight Center, Greenbelt, MD, 20771 USA (Contact: pandagau@msu.edu)

Introduction: It is NASA's goal to implement secure quantum communications within its overall communications architectures. Quantum communications refer to communication systems that are based on quantum entanglement. Quantum entanglement may be realized using photonic and electronic implementations, with complementary roles envisioned for each in space. Entangled photons will be used for secure surface-satellite and satellite-satellite transmissions. Qubits based on spin or superconductivity will be used for secure surface/onboard routing and enhanced processing.

All qubit generation platforms other than ground operation will be impacted by extreme environment operating conditions. The present research focuses on the effects of lunar diurnal temperature variation: 140K (night) to 400K (day, equator) on spin-qubit generation in a heterostructure architecture, with specific focus on changes to magnetic field thresholds required for operation.

Device Architecture: The device architecture is a double layer heterostructure with magnetic swap gate entanglement. The spin-orbit interaction (SOI) provides coupling between spins of electrons held in static or dynamic quantum dots in each layer (Fig. 1).



There is an optimum layer separation distance $z_0 = 2\ell_0$ for spin-spin coupling, whose related coupling strength can be corelated with the time for ideal, magnetically controlled SWAP gate operation that results in spin qubit generation. One original contribution of this work is to also relate z_0 to realistic split gate widths W for device fabrication.

For size weigth and power (SWAP) reasons, magnetic field strength $\bar{B} \leq 5T$ is a serious operational goal. Magnetic SWAP gate operation for spin entanglement is feasible when $\hbar\xi \cong$ 0.02 meV where

$$\hbar\xi = \frac{g_A^2}{\Delta_A} - \frac{g_a^2}{\Delta_a} \qquad (1)$$

with coupling strengths for allowed interactions given by (2):

$$g_A = \alpha\sqrt{\frac{m_{eff}\Omega}{2\hbar}}\left(1-\frac{\omega_c}{2\Omega}\right), \quad g_a = \alpha\sqrt{\frac{m_{eff}\omega}{2\hbar}}\left(1-\frac{\omega_c}{2\omega}\right)$$

with $\Delta_{A,a} = \omega_Z - \omega_{A,a}$. The expressions for Zeeman ω_Z, cyclotron $\omega_c = e|\bar{B}|/m_{eff}$ and center of mass and relative motion related frequencies $\omega_{A,a}$ are written as their equivalent energies.

Two heterostructures with known fabrication protocols are investigated: $Al_{0.3}Ga_{0.7}As$/GaAs (active layer) and $In_{0.85}Al_{0.15}Sb$/InSb (active layer) were previously investigated at room temperature [1]. While InSb demonstrated the lowest magnetic field requirement for spin qubit generation, GaAs heterostructures are attractive for their well-studied fabrication protocol. Equations (1) and (2) show both explicit and implicit dependance on effective mass, which is itself temperature dependent. In the present work, investigations of criteria (1) for spin qubit generation at a given magnetic field strength are investigated for effective mass variations over the lunar temperature range of 140K to 400K. The focus of the investigtions are: (i) to precisely determine magnetic field requirements, to (ii) assess the feasibility of GaAs heterostructures at lower temperatures and (iii) to precisely determine cut-off temperatures for required active cooling at higher temperatures.

[1] Panda, G, Aridi, RS, Dong, H, Ayres, VM, Shaw, HC. Coupled Spin-Orbit Interactions in Flying Qubit Architectures. *2021 IEEE 21st International Conference on Nanotechnology* (NANO), 2021, pp. 409-412.
DOI: 10.1109/NANO51122.2021.9514285.

Acknowledgements:

The support of NASA 80NSSC22K1727 and NASA Michigan Space Grant Consortium 80NSSC20M0124 Subaward #:SUBK00017457 is gratefully acknowledged.

Carbothermal Reduction Demonstration: Laser Driven Reaction in a Thermal-Vacuum Environment and Project Status.

A. B. Author[1] and C. D. Author[2], [1]Affiliation, mailing address for first author, [2]Affiliation for second author, mailing address. (Contact: email address of lead author/primary contact)

Introduction: Lunar regolith is approximately 45% oxygen by mass. The majority of the oxygen is bound in silicate minerals. The carbothermal reduction process has been proven to be effective at removing oxygen from lunar regolith simulants [1]. The Carbothermal Reduction Demonstration (CaRD) project aims to increase the Technology Readiness Level (TRL) of a combined solar concentrator and carbothermal reduction system in order to demonstrate this technology on the lunar surface. The CaRD project is divided into two design cycles, a brassboard and prototype. The status of both design cycles will be discussed, as well as concepts for how this technology can be applied to the Artemis program in the future.

Brassboard Vacuum Test: For the brassboard demonstration, a 2 kW Nd-YAG laser was used to heat lunar regolith simulant within a carbothermal reactor developed by Sierra Space. The reactor was placed inside of a 15ft thermal vacuum chamber at the Johnson Space Center. The resulting reaction products were analyzed using both a gas chromotograph and mass spectrometer provided by Kennedy Space Center.Thermal data was also collected.

Prototype Design: For the prototype, the CaRD team will perform another thermal vacuum test at JSC using the same interfaces and assets developed for the brassboard, but will test a new carbothermal reactor design that Sierra Space is developing through the Carbothermal Oxygen Production Reactor (COPR) Tipping Point project that will include a means to autonomously move regolith in and out of the reactor. In addition, a deployable solar concentrator is being developed by Glenn Research Center using mirrors produced by Carbon Mirror Applications. The solar concentrator will be used to deliver solar energy into a carbothermal reactor to melt regolith and extract oxygen. Avionics and software for the concentrator are being developed by Kennedy Space Center.

Future Concepts: An ongoing task within the CaRD project is to update models that can be used to determine the mass, power, and size of In-Situ Resource Utilization concepts at various scales. These models can now be used to analyze alternatives for future applications based on the latest available data.

References:

[1] Gustafson, R., White, B., & Fidler, M. (2011). 2010 field demonstration of the solar carbothermal regolith reduction process to produce oxygen. In *49th AIAA Aerospace Sciences Meeting including the New Horizons Forum and Aerospace Exposition* (p. 434).

Autonomous Lunar Sitework Robotics: Extensions on the CraterGrader Framework

J. Harrington[1], R. Lee[1], A. Pletta[1], R. Wong[1], B. Younes[1], and W. Whittaker[1]. [1]The Robotics Institute, Carnegie Mellon University, 5000 Forbes Ave, Pittsburgh, PA, (Contact: apletta@andrew.cmu.edu)

Introduction: Rapidly growing international interest in long-term lunar presence requires sustainable surface infrastructure development. In-situ sitework for creation of landing pads, roads, and habitat foundations from existing unstructured and cratered terrain underpins successful construction. Lunar environmental constraints preclude more traditional terrestrial sitework approaches and require autonomy as a key technology for efficient sitework operation.

This work presents the results of an autonomous lunar sitework robot, named CraterGrader, a previously introduced concept for a novel terrain understanding and planning worksystem for autonomous mobile manipulation of deformable terrain to robustly and optimally level terrain while minimizing power consumption for long durations of fully autonomous operation. CraterGrader is the baseline of autonomous lunar sitework, and aims to provide insight towards further development in the field.

System Architecture: The CraterGrader worksystem, seen in Figure 1, is built on a double ackermann four-wheel drive mobility platform with a vertically-actuated grading blade mounted below body-center with a rear-mounted weighted dragmat to aid in smoothing high frequency terrain variation. The flight worksystem would lay in the 50 kg rover class and could be delivered as a payload on a CLPS lander. A robotic total station and a pseudo sun sensor, based on visual fiducial markers, provide externally referenced sitewide positioning. An IMU and actuator encoders provide internal motion feedback, mimicking lunar constraints while utilizing SOTA priors in terrestrial construction autonomy. A front-mounted stereo camera enables online terrain perception for dynamic mapping of deformable terrain.

Figure 1. CraterGrader Worksystem

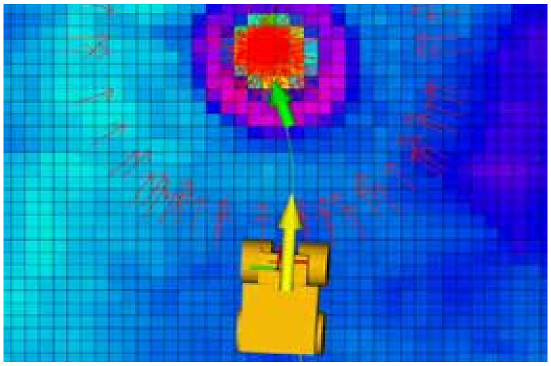


Figure 2. Real-Time Optimal Transport Planner

Autonomy Design: The CraterGrader worksystem enters the designated worksite with no prior topography knowledge. It enters an exploration mode, following a predetermined path considering perception FOV around the site to construct an initial map. The map consists of discretized height grid cells weighted by confidence against new stereo measurements to allow for map updating after eventual terrain modification. Then, CraterGrader uses an optimal transport planner extended from earth mover's distance that calculates a set of waypoints to optimally move map highs into lows to achieve arbitrary design topography, in this case a simple flat plane, while minimizing overall work (Figure 2). Waypoints from the optimal transport plan are passed to an A* kinematic lattice planner to produce feasible mobility paths while avoiding terrain variation. Coupled tool control raises and lowers the grading blade while driving to flatten the crater rim into the valley. The worksystem updates both the map and transport plan online for robust, iterative operation.

Experimental Results: System performance was verified in the 600 sq. ft. Carnegie Mellon University "MoonYard" of surrogate lunar simulant using high-density laser scans to compare initial and final terrain topographies. CraterGrader has successfully shown autonomous grading on roughly 1 m craters and smoothing to satisfy requirements derived from NASA LuSTR specifications, reducing topography RMS below 1 cm while within 1° of horizontal grade in live demonstration.

Conclusions: Autonomy is crucial for lunar sitework enabling sustained lunar infrastructure. CraterGrader has been designed with future lunar research in mind, and is a valuable baseline datapoint in autonomous lunar sitework.

Practical application and testing of regolith parts manufactured with Solar Additive Manufacturing Technology. D. P. Purcell[1] and C. B. Dreyer[2], [1]Colorado School of Mines, 414 Wright Street Apt 107, Lakewood CO, 80228. [2]Colorado School of Mines,1310 Maple Street., GRL 234, Golden CO 80401. (Contact: dpurcell@mines.edu)

Introduction: Additive Manufacturing (AM), and its use on the lunar surface has often only been researched in terms of large-scale construction operations. Technology types have varied, ranging from direct microwave sintering of the lunar surface [1], to polymer composite concrete [2] extrusions for habitats and other structures. A prime consideration for all these technologies is the overall size of both the AM machine, as well as the size of the parts which can be produced. Outward Technologies has developed a Solar Additive Manufacturing system (SAM) that enables production of small-scale regolith parts to be manufactured with in-situ material, for use in infrastructure development as well as for construction projects. Throughout 2022, several lab scale tests were completed at the Colorado School of Mines (CSM) to determine the viability of regolith printed parts produced by Outward Technologies' SAM system, for practical applications. Physical test regimes focused on two areas: Replaceable rover wheel grousers and truss members for tower construction. Interlocking bricks [3] were designed and evaluated with state-of-the-art software designed for AM modeling and simulations.

Wheel Grousers: Grousers are components used to increase traction and manuveravility of rover wheels, similar to the tread of a tire. Grousers were chosen for physical testing due to the numerous advantages offered by having access to custom, AM grousers that could be altered to meet terrain requirements and be produced on demand. Several grouser geometries were designed alongside a custom rover wheel with a shared universal mounting interface that enabled testing of multiple grousers variants. Once outfitted with grousers produced by Outward Technologies' SAM system the custom wheels were mounted onto a small rover (1.1m length x .6m width x 0.6m height, 30kg mass) and driven across CSM's Lunar Testbed. Grousers were monitored for damage during testing, to determine if the regolith parts would be able to survive practical driving conditions when moving through lunar regolith simulants [4]. Physical testing helped identify grouser geometries which were able with withstand driving forces without failure, in addition to providing insight as to how regolith parts should be oriented inside the build volume, in order to provide the best part performance.

Truss Members: Several structures which could be built on the lunar surface with the aid of Outward Technologies' SAM system were identified over the course of the project, and included large towers used for vertical solar arrays [5], and ramps constructed from interlocking bricks. Towers were of a particular interest, as it allowed testing of regolith parts for their interface capability, their strength in compression, and ability to be used in structures that experience complex loading. Two types of construction rods were provided by Outward Technolgies, in order to test multiple methods of assembling complex structures with different interface and tolerance requirements. The final experimental truss was designed and assembled at a desktop scale (143mm long, 143mm wide, 93.25mm tall) with circular regolith truss members loaded at set increments in order to determine the maximum possible load before failure.

Conclusion: Through experimental testing and computer modeling, it has been shown that Outward Technologies' SAM system can produce robust, viable regolith parts, and could be used extensively with in-situ feedstock on the lunar surface. Physical parts were tested for interface capability and strength, providing both qualitative and quantitative data for review. Part applicablilty ranges from small scale interchangeable components such as rover wheel grousers, to large scale members that could be used in tower construction. Outward Technologies' SAM system illustrates how advances in AM capabilities can aid engineers in designing and manufacturing a wide variety of in-situ components on demand.

References:

[1] Taylor, L. A. and Meek, T. T. (2005) *Journal of Aerospace Engineering*, Vol. 18, Issue 3 [2] Lee, T. S. et al. (2015) *Acta Astronautica, Vol. 114, pp. 60-64* [3] Romo, R. et al. (2018) *ASCE, Earth and Space 2018,* pp. 298-96 [4] Taylor, L. A. et al. (2016) *Planetary and Space Science,* Vol. 126, pp. 1-7. [5] Sephora, R. et al. (2022), *Tall Towers on the Moon*.

Autonomous Architectures for Outfitting and Maintenance of Lunar Surface Assets. A. Quartaro[1], and E. Komendera[2], [1]NSTGRO Award Recipient, Virginia Tech Blacksburg, VA 24061, USA, [2]Virginia Tech Blacksburg, VA 24061, USA (Contact: aquartaro@vt.edu)

Introduction: Autonomous robotic operations are critical to establishing a sustained, long-term human presence on the Lunar surface. The Moon to Mars Objectives [1] released by NASA in 2022 further highlight the importance of a strong robotic presence to both enable autonomous construction technologies and optimize crew/science time during crewed missions.

There has been significant momentum to develop lunar robotic systems for cargo transfer, mobility, and ISRU construction in recent years [2]. However, there is not much development in robotic systems that cover outfitting tasks, such as the installation of power lines, life support, and communication lines onto a finished assembled structure, a critical step in construction of any sort.

Heterogenous Conops: The Field and Space Experimental Robotics (FASER) Laboratory is developing autonomous techniques focused on the cable routing aspect of outfitting, within the context of collaborative heterogeneous robotics, to make robotic construction on the Lunar surface a reality.

One example of a heterogenous robot team includes a Long Reach Manipulator, called the Lightweight Surface Manipulation System (LSMS) [3], and smaller dexterous manipulators such as Stewart Platforms (SP). Figure 1 shows both the large scale of the LSMS (Fig. 1b) and the tight profile of a SP (Figs. 1a, 2 inside structural articles). The LSMS performs gross manipulations of objects and SPs around the workspace. SPs and end-effectors can then perform precision jigging tasks, such as cable routing and installation.

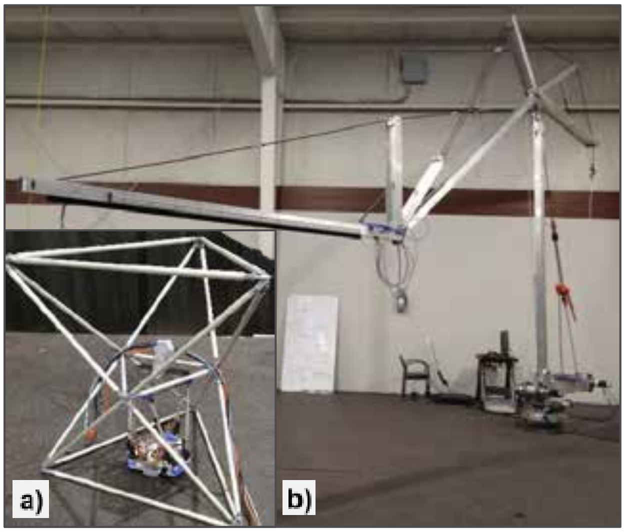


Figure 1: (a) SP for cable routing tasks (b) LSMS

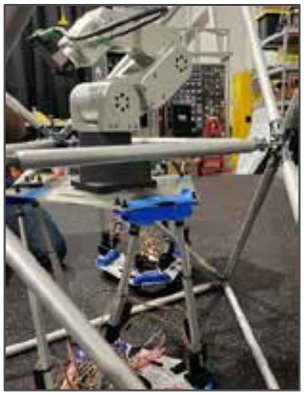


Figure 2: Percision operations in truss

Cable Routing: Robotic cable routing proves to be a complex problem, where a flexible line must be safely maneuvered through a potentially very dense environment, such as scaffolding or a rigid truss structure (as in Fig. 2). Both cable harnesses and structural environment can be damaged by collisions or snags by either the robotic agent or the cable/payload. Structure-Aware Simultaneous Localization and Mapping (SA-SLAM), an online state estimation/planning framework to enable flexible cable manipulation in tight/crowded environments, is being developed to address autonomy gaps in cable routing. Currently in early stages of simulation and testing, SA-SLAM addresses cable routing as an intersection of a variety of fields in autonomous robotics. SA-SLAM must maintain an estimate of the manipulator(s) and how the end effector must move through a cluttered environment, while also tracking and adapting to the dynamic motion of the cable as it's dragged around in a low-gravity environment.

SA-SLAM becomes a part of the larger construction fleet by being implemented on a high fidelity dexterous manipulator, such as the SP+end effector shown in Fig. 2, which can be included in a larger construction/outfitting architecture via collaboration with the LSMS. SA-SLAM is expected to contribute to bridging the gap between high fidelity autonomous technologies and the need for a reduced model for limited in-space computational resources.

References: [1] NASA (2022) *Online: https://www.nasa.gov/sites/default/files/atoms/files/m2m-objectives-exec-summary.pdf,* Accessed 2/14/2022 [2] M. Grande et al. (2021) *AIAA ASCEND* [3] J. Martin et al. (2022) *AIAA ASCEND*

AI-Enabled Autonomy for Lunar Surface Exploration and Commercial Operations.

K. Raimalwala, R. Ahmed, A. Macdonald, E. Smal, M. Faragalli, Mission Control Space Services Inc., 162 Elm St. West, Ottawa, ON Canada, kaizad@missioncontrolspaceservices.com

Introduction: As lunar commerce takes seed and grows this decade following initial technology demonstration and scientific missions delivered via the CLPS program, there will be a growing demand for enabling autonomy for lunar surface operations, which would involve intelligent processing of increasingly large volumes of sensor data, and onboard decision-making independent of direct human oversight. With novel technology to deploy and maintain the use of AI in spaceflight, Mission Control is pioneering how lunar missions can embed AI in their systems.

Technology Overview: Spacefarer AI

Within the field of Aritificial Intelligence (AI), Deep Learning techniques are the leading standard in terrestrial applications that require computer vision and natural language processing [1]. However, they are power intensive so they must be customized for space hardware. The software tools hardware vendors currently ship are difficult to install and use, and represent a pain point in developing and deploying mission critical components for our customers (including our internal customers). This fragmentation of the software landscape into hardware vendor specific run-time tools and compilers prevents innovations from spreading broadly within the AI community [2]. To address these challenges, Mission Control has developed the Deep Learning Accelerator (DLA), a multistage deep learning compiler and corresponding run-time for accelerating neural network inference. The DLA is a key component of Spacefarer AI: Mission Control's emerging product line of tools to facilitate deployment of AI models in spaceflight.

Flight Demonstrations: On December 11th 2022, Mission Control's MoonNet AI payload launched onboard the first ispace mission M1. Slated to land and begin operations some time in Q2 2023, MoonNet will be the world's first demonstration of Deep Learning on the lunar surface, a historic milestone for space exploration. It will classify lunar surface features visible in images from the Rashid rover in the Emirates Lunar Mission (ELM). Mission Control will also participate in the international science collaboration of ELM, led by the Mohammed Bin Rashid Space Centre (MBRSC). Following this critical demonstration of AI-based autonomy, Mission Control is eager to deploy this technology for future lunar surface prospecting and ISRU missions.

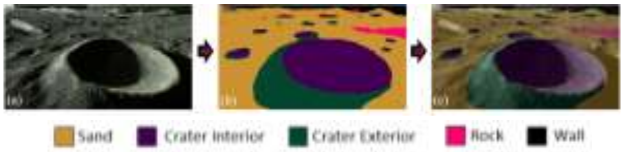


Figure 1. Example output of our MoonNet lunar terrain classifier, trained on images of our lunar testbed.

Mission Control is currently also engaged with the European Space Agency to complete an AI demonstration onboard ESA OPS-SAT, a satellite already in space and launched specifically for AI experimentation and demonstration.

More details on these flight demonstrations can be found in recent publications [3-5].

Autonomy for Future Lunar Missions

AI-powered applications can enable autonomous tasks for lunar systems such as:

- Autonomous perception of the lunar environment can support autonomous navigation for lunar rovers and other ground vehicles, as well as autonomous targeting for onboard scientific payloads andactuation such as scooping, drilling, and robotic arm operations.
- Detection of anomalies/faults for any system ranging from an excavator vehicle to an ISRU processing plant.
- Intelligent prioritization of data to downlink to Earth for improving the efficiency of missions that produce high volumes of data but need to extract relevant information in a timely manner.

While for the near future, computationally intensive training processes for AI will be conducted on Earth, in the future we will also see the rise of lunar data centers and infrastructure and power to facilitate training on-site or even at the edge, i.e. close to the point of operations. Mission Control is currently exploring methods to facilitate architectures with on-site learning for AI models.

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

References:

[1] Zhang D. et al. (2022) *AI Index 2022 Annual Report* [2] Lattner et al. (2019) [3] Raimalwala K. et al. (2022) *IAC 2022*. [4] Ahmed. R. et al. (2022) *IAC 2022*. [5] Macdonald A. et al. (2022) *ASCEND 2022*.

X-energy Microreactor Program and Synergies with Space Nuclear. D. J. Rhodes and B. T. Rearden, X Energy LLC (X-energy), 801 Thompson Ave., Rockville, MD. 20852 (Contact: dov.rhodes@x-energy.us)

X-energy presents progress on its commercial microreactor known as XENITH; *X-energy Next-generation Integrated Transportable Hight-temperature* microreactor. We present an overview of the XENITH system and commercialization roadmap, while highlight key enabling technologies that are common to both the terrestrial microreactor development and our space nuclear programs.

The XENITH is a compact, 20 MWth heat source coupled with a power plant that will supply 5 MWe of net electricity to remote communities, mining sites or disaster zones, and hospital or college campuses in addition to 10 MWth of hot air for driving district heating or other low temperature thermal processes. This effort leverages experience and lessons learned from Project Pele, supported by $45M of DOD investment and another $20M of internal X-energy funded R&D. Pele resulted in an expert research and development team that is now developing a commercial design with a focus shifted from extreme performance (per DOD requirements) to a cost effective design that will compete with diesel for off-grid users.

The modular architecture of XENITH allows periodic replacement of the Nuclear Reactor Module (every 3-5 years depending on the demand) while reusing the balance of plant and site infrastructure with minimal down time. Integrated module shielding enables safe access to systems for inspection and maintenance. The modularity of the design also offers potential for swapping out components for a space-based reactor supporting Nuclear Electric Propulsion (NEP) for interplanetary travel.

A common technology to new terrestrial and space nuclear projects is the fuel. A high safety pedigree is achieved by partnership with X-energy subsidiary fuel provider *TRISO-X*, which has already demonstrated its ability to fabricate robust TRISO coated particle fuel. The kernels of the mm-scale coated fuel particles will contain uranium enriched up to 20%to achieve a burnup comparable to that attained in much larger light water reactors. TRISO coated fuel particles retain radionuclides even under extreme accident conditions. TRISO-X has successfully demonstrated its quality production process under a $>53M DOE-funded project, with partnership from Oak Ridge National Laboratory. This process has its origins in the >$350M, 20-year investment in TRISO fuel qualification by the DOE. TRISO-X is presently engaged in NRC licensing and construction of a commercial fuel fabrication facility. A common form factor of TRISO fuel is under development to support all forms of space nuclear, including NEP, FSP, and even NTP (Nuclear Thermal Propulsion).

Another synergistic technology development is our Digital Control System (DCS) and Digital Twin (DT). This effort was kickstarted by a $6M ARPA-E grant to support X-energy's flagship grid scale power plant, the Xe-100. It was then adapted to microreactor applications through Project Pele, and is now being pivoted to support FSP under a $5M contract from NASA, shared by X-energy and partner Intuitive Machines. Highly robust control and automation is of paramount importance for any transportable reactor system – terrestrial or space based – that operates with little to no operator involvement. By integrating the development of our DCS and DT using Model Based Systems Engineering (MBSE) principles and a common computing framework, we ensure that the DCS and DT simulator are fully consistent and mutually supporting. Modular implementation supports gradual introduction of Hardware in the Loop (HiL) and Software in the Loop (SiL) infrastructure, increasing technology readiness level (TRL) over time. This approach will streamline Verification and Validation (V&V) of new control systems while providing a testbed for scenario development and training.

Lastly we present an overview of the design methodology and toolkit common to research and development of all of X-energy's advanced microreactor and space nuclear systems. X-energy's Government R&D Division showcases a unique workflow that balances agile multi-disciplinary design with the rigorous requirements for nuclear quality and safety. The workflow leverages nuclear qualified tools, existing V&V, and a tightly coupled data flow between them, including design and analysis tools for modeling neutronics, reactor kinetics, thermohydraulics, thermodynamics, mechanical, and electrical systems. These tools also support DCS and DT development. The combined workflow and toolkit facilitate rapid design prototyping of new designs and creative generation of cutting-edge solutions for advanced nuclear systems, both terrestrial and in space.

Modular Robotics: A Method for Reducing Barriers to Lunar Initiatives. C. W. Rosén[1], S. P. Dougherty, and Z. T. Nishino [1]Maxar, 1300 W. 120th Ave, Westminster, CO 80234. (Cameron.Rosen@Maxar.com)

Introduction: One of the largest barriers to the creation of a sustained lunar presence is the absence of affordable technology enablers [1,2] such as robotics. Some of the key lunar initiatives, including regolith study [3], regolith and geologic terrain inspection [4], and manufacturing are achieved by robotic and mobility platforms. Actuation and manipulation are necessary to sift regolith, orient cameras and sensors, and move materials. Further, robotics bolsters the capabilities of astronauts on the lunar surface by executing tasks autonomously and providing additional dexterity and tools.

Maxar directly addresses the affordability and accessibility of robotics for lunar and space applications with its next-generation modular robotic platform. This platform provides a robust hardware and software architecture that can be easily adapted to a variety of mission needs. Specially designed "building block" modules allow for the repetition of tube, joint, and actuator designs, as well as flexibility in software design.

Figure 1: SAMPLR Robotic System

As an advancement from the six Maxar robotic arms on Mars, the SAMPLR (Sample Acquisition, Morphology Filtering, and Probing of Lunar Regolith) mission provides a fully realized, flight version of this modular robotic architecture and software (Figure 1). The SAMPLR system will perform lunar regolith science via a robotically actuated vision system, penetrometer, and regolith scoop and sieve on a future NASA Commercial Lunar Payload Services (CLPS) mission. This next generation system also provides the flexibility needed for inclusion on autonomous and manned rovers, such as NASA's Lunar Terrain Vehicle (LTV) as well as any other small to large-class mobility platforms.

Hardware Modularity. Maxar's modular architecture focuses on the use of repeated structures, mechanisms, electronics, and interfaces. Distributed motor control boards (MCBs) collocated with actuators at joints are a critical part of this design concept, providing scalability to a key robotic building block. Figure 2 illustrates the modular bi-axial joint that is integral to Maxar's next-generation robotic platform, and is also highlighted in Figure 1. The economies of scale further benefit repeated structures and their components – allowing for streamlining of processes, qualification, and analyses efforts. Each module can be analyzed once with typical lunar parameters for structural, thermal, electrical, workspace, and more, but can always be tailored to specialized environments as needed. Repeated mechanisms and structures also allow for procurement and assembly efficiencies, as items can be purchased, kitted, and assembled in a standardized fashion. Other hardware components benefit from this modularity as well, including arm tubes, harnessing, and thermal blanketing.

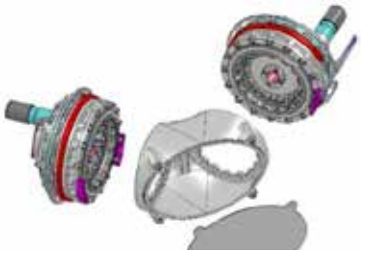


Figure 2: Modular Bi-Axial Robotic Joint

Software Modularity. Modular, standardized interfaces are used in developing Maxar software, so that the same robotic software suite can be leveraged for any design or mission need. System agnostic sensor and sub-system interfaces allow for rapid scalability – requiring only driver development for new components.

The benefits provided by this modular robotics approach, including design and application flexibility, as well as cost reduction will be integral in lowering the barriers to lunar initiatives.

References: [1] El Samid, N. A., et al., (2008). Infrastructure Robotics: A Technology Enabler for Lunar In-Situ Resource Utilization, Habitat Construction and Maintenance. In *Proc. of Intl. Astronautic Conf*. [2] NASA (2016), *Strategic Knowledge Gaps*. [3] M.A. Siebert et al., (2020) Sample Acquisition, Morphology, Filtering, and Probing of Lunar Regolith (SAMPLR) Payload. *51st Lunar and Planetary Sci. Conf.* [4] Raimalwala, K. et al., (2020). *Onboard Sci. Autonomy for Lunar Missions: Deep-learning Based Terrain Classification and Novelty Detection* (No. EPSC2020-405). Copernicus Mtgs. (1997)

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.

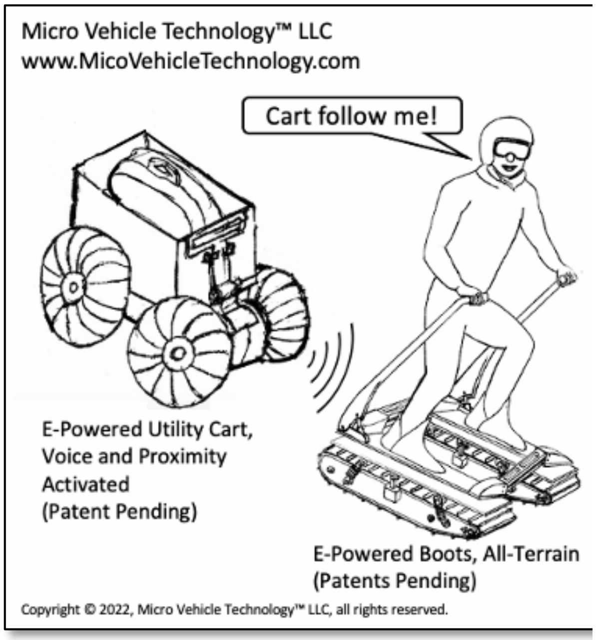
The Innovation:

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.



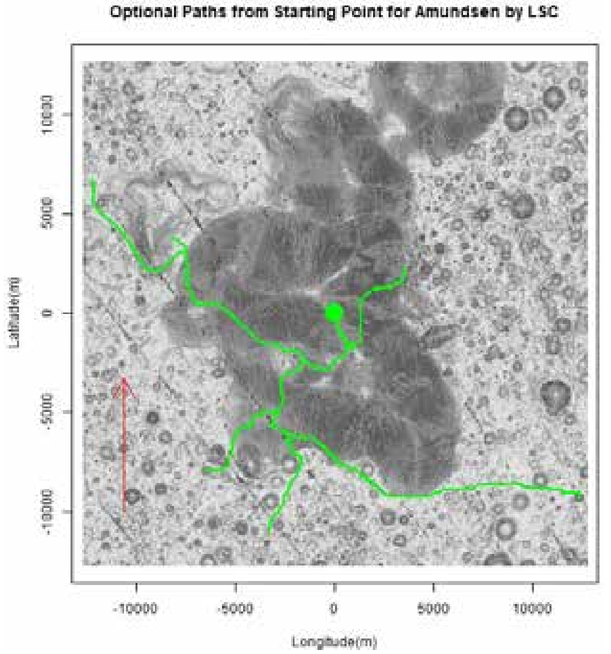
- Powered Boots Micro Vehicles™ reduce the need for astronauts to walk and sit, thus mitigate health and constricted spacesuit concerns.
- Use of Powered Boots Micro Vehicles™ will cut out much time from the already planned Artemis III xEVA Con Ops walking range or may allow additional activity and greater 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, surface travel routes, colonization, and operations can be expedited and optimized for efficiency and fault tolerance.

[1] Rudofsky K.M. (2021) *United States Patent and Trademark Office, Application No. 17238202 - Powered Boots*

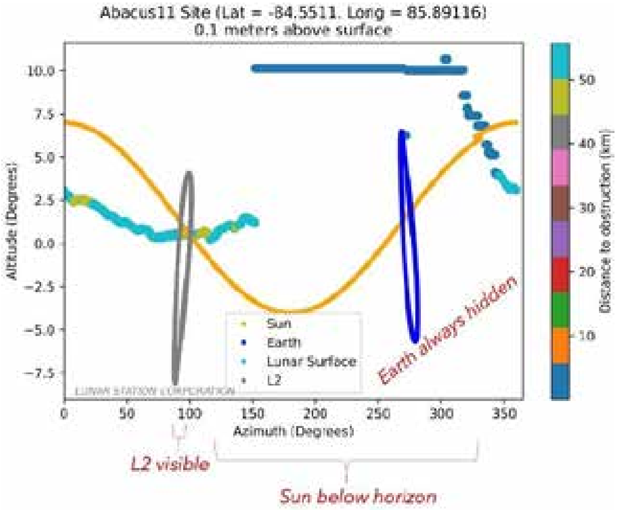
[2] Rudofsky K.M. (2021) *United States Patent and Trademark Office, Application No. 17241060 Utility Cart, Electric Powered, Voice and Proximity Activated.*

MoonHackerTM Lunar Data Analytics: A Case Study for Exploring Amundsen Crater. K. D. Runyon[1] B. DeWitt[2], D. Williams[2], F. Jenet[2]. [1]Planex.space – Planetary Experience Consulting LLC (kirby@planex.space), Ellicott City, MD USA; [2]Lunar Station Corporation (LunarStation.space), Cambridge, MA.

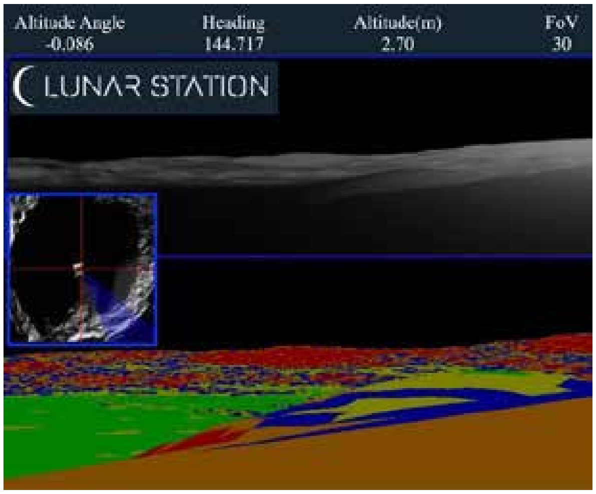
MoonHacker™, the proprietary software of Lunar Station Corporation (LSC), is a geospatial analytics engine that ingests large, disparate lunar datasets and provides powerfully derived products to facilitate immersive and comprehensive understandings of the lunar domain. MoonHacker™'s analytics provide solutions for: lunar surface mobility; access to extreme environments; analysis of lunar surface lighting conditions; communication site lines; mineralogy; terrain characterization; space weather; thermal management; and many other analyses as well [1]. The impact of lunar data analytics will play an increasingly larger role in the lunar economy [2]. MoonHacker^{TM} is wellpositioned to facilitate this economic and exploratory growth. Here, we reveal a case study of an Artemis-inspired, crewed exploration campaign of the Moon's Amundsen Crater to demonstrate MoonHacker^{TM}'s analytical capabilities.



Above: All possible paths originating at the landing site (Amundsen Crater's central peak) on as determined by a Monte Carlo simulation constrained to slopes 25° or less with a weighted average favoring increased illumination. The axes are in meters, ticked at 5000 m increments.



Above: Astrometry plot showing a 360° view around the landing site indicating the position of Sun, Earth, and L2 relative to visible topography over a lunar day. Any other celestial feature or any future dataset, such as the Geo satellite belt, could be included.



Above: Two simulated views (natural, top; slope map, bottom) of the south-western wall of Amundsen as seen from a point along the traverse.

Contact Lunar Station Corporation (info@lunarstation.space; dennis@lunarstation.net) to discuss your requirements and learn more about LSC's advantages for custom analysis of your specific slice of the Moon.

References: [1] **Kornuta**, D., et al. (2019). Reach, 13, 100026. [2] **Scatteia**, L., and Perrot, Y. (2019). Research paper prepared by PwC. https://www.pwc.com.

Lunar Temperature Effects on Polarization Qubit Generation by SPDC.

N. Sebasco[1], G. Panda[1], J. Vetere[1], V.M. Ayres[1] and H.C. Shaw[2], [1] Department of Electrical & Computer Engineering, Michigan State University, East Lansing, MI 48824 USA, [2]Code 5560, NASA Goddard Space Flight Center, Greenbelt, MD, 20771 USA (Contact: sebascon@msu.edu)

Introduction: NASA has vital interests in secure long distance, high speed, free space transmission and retrieval of data supporting initiatives such as Lunar Gateway (a vital component of NASA's Artemis program), Deep Space Quantum Link (DSQL) and long-term human return to the lunar surface. . In addition to radical new communication protocols, breakthroughs in quantum entanglement could lead to new discoveries that support high precision measurement via distributed quantum sensing that are relevant to complex and dynamic situations. Breakthroughs in quantum communication translate readily to quantum computing, making these investigations a potent source of technology transfer opportunity.

Quantum entanglement refers to the inseparable nature of certain multi-particle states where interaction with one particle in the system immediately influences other particles in the system regardless of how far apart the particles are separated. This is radically different than in classical mechanics where the degree of influence would attenuate as the degree of separation increases. For quantum communications to become reality, it is important to discover what happens to quantum entanglement when departures from controlled conditions are present. The present research focuses on predicting the possible effects of lunar diurnal temperature variation: 140K (night) to 400K (day, equator) on SPDC-based polarization qubit generation for lunar surface to satellite secure communication.

Polarized Qubit Generation Method: Higher frequency photons from a sufficiently high intensity source (a laser beam termed "pump: p") may spontaneously convert inside a non-linear birefringent crystal into pairs of lower-frequency photons ("signal: s" and "idler: i") in a process termed Spontaneous Parametric Down Conversion (SPDC). In its most basic configuration, SPDC can be used to produce polarization entangled photons by utilizing the coherent spatial overlap of the lower frequency s and p photons. This requires meeting both conservation of energy and momentum requirements and polarization phase matching requirements that result in measurable ouput. Single crystal SPDC efficiency is not high and in controlled laboratory settings, the current state of the art is to increase it by using multiple nonlinear crystals and/or multiple crystals with specific internal orientations, all carefully aligned with respect to each other. However, the simpler basic design could prove more robust under extreme environment conditions and is the subject of the present investigation.

The efficiency of the SPDC process is proportional to $sinc^2\left[\Delta k_z \frac{L}{2}\right]$. Efficient entanglement depends on achieving the best wave vector match: $\Delta k_z = \left(k_{sz} + k_{iz} - k_{pz}\right) \approx 0$ for polarization entanglement criteria derived in tutorial article reference [1] that depend on the nonlinear crystal thickness L, the distance of Gaussian laser beam waist to the nonlinear crystal entry face d as shown in Fig. 1 and a crystal rotation θ_p with respect to the internal nonlinear crystal fast axis (not shown) required to accommodate polarization matching.

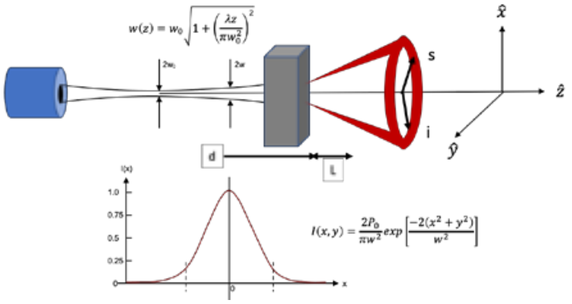


Figure 1. SPDC with Gaussiam laser beam.

Results:

A β-bismuth barium borate (BBO) crystal of room temperature thickness 2 mm is under investigation to assess how changes to d and L over the lunar 140K to 400K min-max temperature range impact the θ_p polarization matching requirement and whether conditions for entanglement can be met over the whole temperature range. The BBO crystal is a single crystal version of the bi-crystal set-up in the Quantum Communications Laboratory at the NASA Goddard Space Flight Center (GSFC). A 100 mWatt pump laser at 405nm is investigated first to benchmark room temperature predictions within the range to those in reference [1], followed by doubling to 810nm to match the NASA GSFC pump source.

References: [1] S.Karan et al J. Opt. 22 (2020) 083501 (20pp). DOI: 10.1088/2040-8986/ab89e4

Acknowledgements: The support of NASA 80NSSC22K1727 and NASA Michigan Space Grant Consortium 80NSSC20M0124 Subaward #:SUBK00017457 is gratefully acknowledged.

Lunar Regolith Tolerant Connectors: Resistance is futile, so assimilate and overcome. Ritch A. Selfridge, Senior Technology Engineer, Amphenol Aerospace. 191 Delaware Avenue, Sidney, NY 13838. (rselfridge@amphenol-aao.com)

Introduction: The Apollo missions provided insight into the detrimental impacts of lunar regolith on mechanisms and interfaces meant to be engaged and separated repeatedly. Lunar bases will be composed of components which will require assembly on the lunar surface. In addition to lunar base components, lunar vehicles and robots will also require electrical connections for power and data transmission. With reliability and size/weight at a premium, lunar connectors will need to function in the presence of lunar regolith, as well as the other extremes of the lunar surface environment. Wireless/contactless connectors have potential advantages, but have added complexity and therefore potential reliability concerns. Seals, caps, and shutters may initially provide protection against lunar regolith intrusion into a connector's mating interface, but typically become sources for contamination and/or failure after multiple engagements and separations. With the thought of keeping it simple, a unique robust contact system has been evaluated when repeatedly exposed to lunar regolith simulant LSM-1. Based on this initial testing, an evolved variant of this contact system and a connector have been proposed for future development and consideration.

Excavation of Lunar Regolith and In-Situ Oxygen and Metal Extraction. N. B. Singer[1], Z. Tanaka[1], and N. Netzer[1] [1]Diatomic Space Incorporated, 15 Granada Cres, Unit 6, White Plains, NY. (Contact: noah@diatomicspace.com)

Introduction: Diatomic Space Incorporated (DSI) is developing a lunar in-situ resource utilization (ISRU) system incorporating the *Hydra* excavator rover and an ionic liquid chemical reactor for resource extraction. The ISRU system will produce 2,000 kg of oxygen and 1,000 kg of useful metals (iron, aluminum, titanium) per year in support of a permanent human presence on the lunar surface.

Hydra Rover: The *Hydra* excavator rover uses bucket drum technology developed for the RASSOR excavator [1]. DSI is licensing this technology from NASA KSC. *Hydra* is 4-wheeled rover which can operate both right-side up and upside down. It uses 16 individual bucket drums to efficiently excavate lunar regolith, storing the excavated regolith inside the rotating drum. The material is dumped from the bucket drums by reversing the direction of rotation. *Hydra* can be deployed in a swarm of up to 8 rovers, coordinating their activities and providing assistance (such as rescue) to each other when needed.

Chemical Reactor: DSI is developing an ionic liquid-based chemical process for extracting oxygen and metals from lunar regolith, extending initial work completed at NASA Marshall [2]. Initial work with choline-based ionic liquids have shown promising results, including the generation of gaseous oxygen and the plating of iron material from regolith slurry. Work is now proceeding to further characterize this process, investigate additional ionic liquids and to extract additional target metals such as aluminum and titanium. This process is capable of operating on both mare and highland regolith.

References:

[1] J. M. Schuler, et al. (2019) *RASSOR, the reduced gravity excavator* [2] E. T. Fox, et al. (2018) *Ionic Liquid Facilitated Recovery of Metals and Oxygen from Regolith*

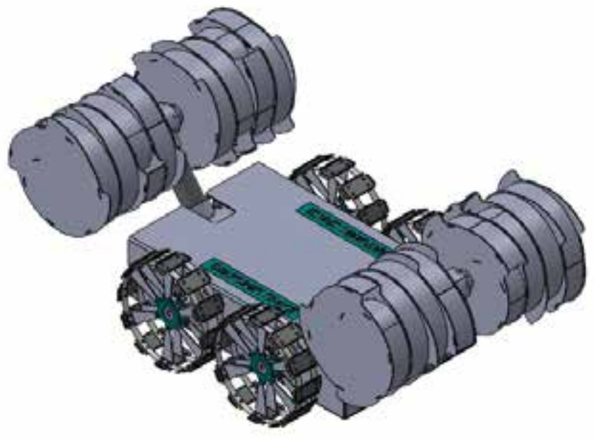


Figure 1: *Hydra* excavator rover.

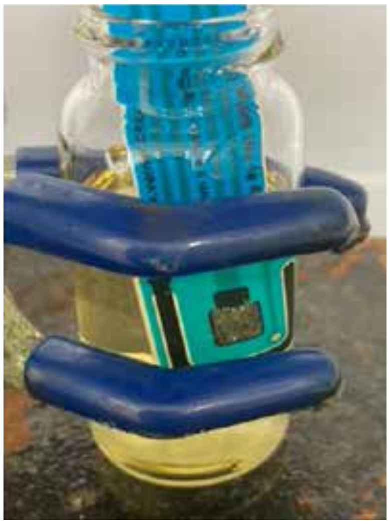


Figure 2: Generation of oxygen gas from lunar regolith digested in the ionic liquid EMI HSO_4.

Evaluation of combined Electrodynamic Dust Shielding and bristle based mechanical cleaning as a method of lunar dust mitigation for irregular surfaces.

K. G. Sjolund[1], M. J. Schaible[1], T. M. Orlando[1], and J. S. Linsey[1], [1]Georgia Institute of Technology, 901 Atlantic Dr. NW, Atlanta GA 30318. (Contact: juile.linsey@me.gatech.edu)

Introduction: With the Artemis missions planning to establish long-term habitation on the lunar surface, a robust suite of lunar dust mitigation techniques require development. One particular form of dust mitigation is Electrodynamic Dust Shielding (EDS). EDS works by providing a high voltage AC signal at low frequencies to alternating electrodes, creating small electric fields that move dust grains via coulombic and dielectrophoretic forces. [1,2] Existing studies have shown EDS to be effective at cleaning flat or gently curving surfaces such as astronaut visors photovoltaic cells. [1] However, there is growing interest in developing EDS for flexible and irregular surfaces such as spacesuits. [2]

This research proposes further development of 3D-EDS, or EDS that affects a volume rather than a surface. The concept was originally developed by Shoot for the Moon, a student team at Georgia Institute of Technology, for NASA's 2021 BIG Idea Challenge. To accomplish this, the interspersed electrodes were aligned with the bristles of a brush so that the resulting electric fields affected dust grains that accumulated in the bristles. Such a technique would further expand the suite of dust mitigation technologies for the Artemis missions.

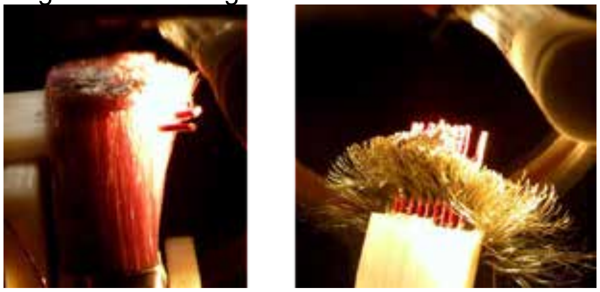


Figure 1: 3D-EDS experiments conducted by Shoot for the Moon for NASA's 2021 BIG Idea Challenge. Experiments were conducted in vacuum with LHS-1 lunar simulant, copper wire and a nylon brush (left) and Thunderon® brush (right) Heating from a UV light caused the bristles to melt.

Experiment Design: Previous experiments, such as those shown in Figure 1, were conducted to evaluate the ability at which EDS can remove lunar dust simulant from a brush. These experiments inserted parallel copper wires into a premade brush and applied a 2-phase AC signal at 60Hz. While these experiments demonstrated that 3D-EDS could cause some dust movement, significant improvements to experimental design were required.

A new experiment has therefore been designed to better explore the capabilities of 3D-EDS. This design also used premade brushes but had copper wires aligned with the bristles instead of inserted at an angle to the bristles. Additionally, the wires were arranged as an array within and around the bristles and could be used in both two and three phase EDS signals. Figure 2 shows a model of the new experimental setup. While experiments using the new apparatus are currently in progress, it is expected that dust grain movement will increase and will be directed perpendicularly out of the bristle clusters.

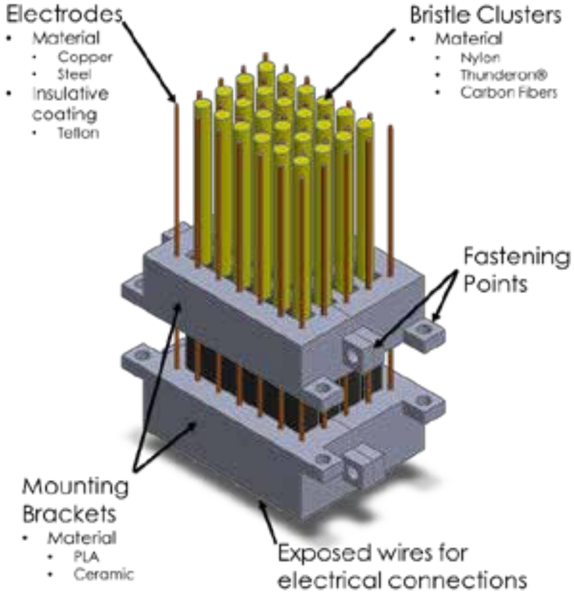


Figure 2: Rendering of the current 3D-EDS testing apparatus.

References:

[1] Afshar-Mohajer, N., et al. (2015). *AiSR,* 56(6), 1222-1241. [2] Manyapu, K. K., et al. (2019). *Acta Astronautica,* 157, 134-144.

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

Off-the-shelf Resource Prospecting Services for Landers and Rovers.

P. Sobron[1,2] and A. Wang[3], [1]Impossible Sensing & [2]SETI Institute, 2700 Cherokee St, St Louis, MO, [2]Washington University in St Louis, One Brookings Dr, St Louis, MO. (Contact: psobron@impossiblesensing.com).

The Reality: The Moon has the resources we need to build structures, support humans, and power rockets locally. The Moon might be our getaway to deep space because launching rockets from there is much easier and has zero environmental impact. The problem is that we need to learn where those lunar resources are; at best, we know the location of water deposits with a precision of 10s of kilometers. So, before digging on the Moon, we must explore it intensively.

The Solution: The only way to do this is to upgrade landers, rovers, hoppers, and astronauts from mere photographers to prospectors. Missions to the Moon are very complex and, for the foreseeable future, only last a few weeks, so prospecting solutions—including CLPS—must explore as much ground as easily and quickly as possible. This means delivering high-resolution resource maps on the fly without sampling and processing regolith. Three techniques can do this:

Technique	Speed	Sensitivity	Selectivity	Spaceflight Maturity
Raman spectroscopy	Medium	High	Medium	Medium
LIBS (laser-induced breakdown spectroscopy)	Fast	High	High	Medium
Mid-infrared reflectance spectroscopy	Fast	Medium	Low	High

- Speed: [Fast] Results in seconds. [Medium] Results in minutes.
- Sensitivity: [High] Detection of 1% w/w or lower. [Medium] Detection of 5% w/w or higher.
- Selectivity: [High] Distinguish different compounds. [Medium] Distinguish some species, but not all. [Low] Limied ability to distinguish species.
- Spaceflight Maturity: [High] Successfully used in spaceflight missions. [Medium] Used in some spaceflight missions, but further development and testing may be needed.

.

Technical Capabilities of Our Team: We have matured Raman spectroscopy instruments to TRL 5/6 under DALI and MatISSE that can, among others, fingerprint minerals in the plagioclase, olivine, pyroxene oxide, spinel, sulfides, and phosphates groups; characterize hydrogen-bearing and organic volatiles; and fingerprint and quantify the abundance of H_2O and hydroxyl—they can do this because each compound has a unique molecular structure and vibrational fingerprint, and the instruments are sensitive enough to analyze them. They can be mast- or arm-mounted on landed craft.

Under SBIR, we have matured LIBS technology to TRL 6. Our LIBS system can detect and quantify the abundance of virtually all elements in the periodic table. It is optimized to prospect for priority ISRU commodities such as KREEP, Th, U, Ca, Hg, and Mg. We are also assembling a TRL 4 LIBS that embeds in a drill bit to enable LIBS-as-you-drill real-time resource prospecting of the lunar subsurface. This LuSTR project aims at enabling robotic 3D prospection with small rovers.

ASTID, MIDP, PIDP, and ASTEP funded the development of our TRL 6 mid-IR reflectance spectrometer. Less than 1 kg in mass, this ultra-compact system can be deployed from 30 cm or housed in a rover wheel to perform surveys of the same molecular compounds that Raman can but 10x faster—with lower sensitivity and selectability.

We are also furthering the analytics side: we have developed capabilities to turn real-time data into compositional knowledge. In practice, our analytics tools are making our Raman, LIBS, and mid-IR instruments off-the-shelf services for resource prospecting on the Moon, where autonomous rovers will mount different measurement devices, each optimized for specific exploration tasks. We're using CNNs—convolutional neural networks—that self-learn from the instruments and environment.

At the conference, we will review the performance metrics of our suite of intelligent prospection services and show examples of operation in high-fidelity use cases.

GITAI LUNAR ROVER AND ROBOTICS ARM FOR LUNAR EXPLORATION AND BASE CONSTRUCTION. T. Kozuki[1,] R. Ohira[2], R. Ueda[1], S. Kitano[1], N. Ito[2], T. Terada[2] K. Nakamura-Messenger[1] Y. Nakanishi[1] and S. Nakanose[1] [1]GITAI USA Inc. 2255 Dominguez Way, Torrance, CA 90501.[2]GITAI Japan Inc. 1-20-13 Haneda, Ota, Tokyo, Japan, (t.terada@gitai.tech)

GITAI provides labor in space: GITAI Inc. [1] is developing general-purpose robots for a wide range of tasks in the harsh space environment. In the short time since its founding five years ago, GITAI successfully executed a robotic arm demonstration in the International Space Station [2]. Another arm demo is scheduled outside the ISS in 2023. GITAI is also a partner for developing a pressurized lunar rover with Toyota, as part of an agreement between JAXA and NASA. GITAI is developing robots to perform and/or support astronaut EVA activities, including assembly, inspection, maintenance, and repair in orbit and on the lunar and Martian surface. GITAI robots achieve affordable mission costs and promote crew safety by reducing crew exposure to hazards.

Here we describe GITAI's versatile Lunar rover, designed to support activities including payload mobility and deployment, sample collection, in situ resource utilization support, and lunar base construction.

Control modes: Capabilities include both remote virtual reality control and autonomous action. Dual arms with grapple end effectors: These can perform simple, repetitive, or time-consuming precision operations such as offloading support, mating connectors, and off-loading support capability (Fig.1).

Fig. 1: Offloading support of a large structure by GITAI Rover robot at JAXA/ISAS lunar test field; successfully removed shackles and slings from the structure.

Mobile arm with tool changer (Fig.2, 3): Developed by GITAI, this arm has the capability to reposition itself to multiple grapple fixtures on the rover and lander. It achieves this by "walking" end over end from one fixture to another (Fig.2). The arm can receive power and data from either end. It can perform a wide range of tasks including excavating, chipping (Fig.3), and sampling (scooping regolith and picking rocks) and deposition into a collection mechanism.

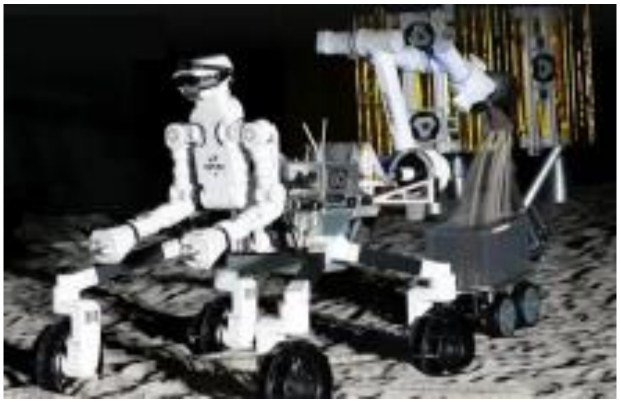


Fig. 2: GITAI Rover with a re-positionable arm, pouring sandy sample into a sample container.

Fig. 3: Percussive sample fragmentation. All images are real demonstrations, not renderings.

The future: GITAI has a strong record of rapid development of highly capable robotic systems for flight, mainly due to our all-in-house approach to both hardware and software. GITAI can accommodate aggressive schedule and technical needs, including end to end integration and immediate software adjustments.

References: [1] https://gitai.tech/ [2] GITAI Press Release (2022) [3] Space News (2022)

Approved for public release, NGA-U-2023-00185

Towards an Operational Lunar Reference System.

A. D. Terry[1] [1]National Geospatial-Intelligence Agency, Office of Geomatics, 3838 Vogel Rd, Arnold, MO 63010. (Contact: alexandria.d.terry@nga.mil)

Introduction: Safe lunar surface navigation will require a Lunar Reference System (LRS), including a reference frame and environmental models. A reference system is the enabling technology for positioning and navigation with the purpose of ensuring that various technologies reach the same point. As such, it is more than just a simple orthogonal reference frame and must define all of the relevant surfaces and necessary environmental models needed to navigate. It is also important to publish a standard description of the refence system in order to enable different vendors to build equipment to operate within that system.

Authority: The National Geospatial-Intelligence Agency (NGA) is Congressionally mandated to improve navigational safety and provide mapping and charting. This mission extends to wherever the US government needs to safely navigate, in this case the lunar surface.

On Earth, the official terrestrial reference system for the DoD is the World Geodetic System 1984 (WGS 84), produced by the NGA. WGS 84 is a dual use technology with 4 to 5 billion users daily and because it is the reference system for GPS, most users don’t even realize they are using WGS 84. In addition, all DoD maps and charts are in this reference system. The LRS would be a comparable product for the Moon.

The Lunar Reference System: On the lunar surface, where standard, low-tech navigation methods such as a map and compass may not be available, equivalent environmental measurements and models will become even more important. Lunar missions have provided multiple data sets of varying resolution and overall quality. These data sets have been modeled, mostly independently of each other, over many years, but gaps remain in achieving the accuracy required for navigation.

NGA is starting from NASA’s current Lunar Reconnaissance Orbiter (LRO) reference frame and the GRAIL gravitational model and refining them into a publishable standard. This effort includes refining the gravity model to support inertial navigation systems and generating other environmental models to support as many different types of navigation technologies as possible. Additionally, the LRS Working Group is exploring strategies to improve the reference system including establishing additional lunar realization points.

This presentation will introduce the LRS and compare the current state of the lunar reference frame and environmental models with WGS 84 in order to demonstrate what will be needed to safely navigate on the Moon.

The SAMPLR Specialized Penetrometer. B. C. Thrift[1] and C. B. Dreyer[1], [1]Center for Space Resources, Colorado School of Mines, 1310 Maple St GRL140, Golden, CO, 80401. (Contact: benthift@mines.edu)

Introduction: The Sample Acquisition, Morphology filtering, and Probing of Lunar Regolith (SAMPLR) payload is a robotic arm and instrument suite that are manifested on a future Commercial Lunar Payload Services (CLPS) mission to the Moon. SAMPLR is a collaboration between Maxar Technologies, NASA's Goddard Spaceflight Center, and the Colorado School of Mines Center for Space Resources as part of NASA's Lunar Science and Instrument Technology Payload (LSITP) program. [1]

The SAMPLR instrument suite includes a specialized penetrometer. This specialized penetrometer is a lightweight and relatively simple instrument that provides a large amount of in situ geotechnical data. The SAMPLR penetrometer will be used to aid in the determination of geotechnical properties and the characterization of lunar regolith. The penetrometer can also assist in identifying the presence of ice in lunar regolith. This specialized penetrometer instrument would be an asset for both the ISRU and Excavation/Construction focus areas. Specialized penetrometer data are being collected and analyzed at the Colorado School of Mines in support of the SAMPLR payload mission.

Materials and Methods: Specialized penetrometer tests and techniques are being developed using the ISRU Experimental Probe (IEP) and a uFactory xArm robotic arm. The IEP was developed at the Colorado School of Mines as a part of the Institute for Modeling Plasma, Atmospheres, and Cosmic Dust (IMPACT) of NASA's Solar System Exploration Research Virtual Institute (SSERVI) [2]. The IEP consists of a zero backlash three-axis translation stage, a highly sensitive force-torque sensor, and a probe. The IEP is contained in a dusty vacuum chamber and liquid nitrogen chilling capabilities to allow experiments to be conducted in a lunar like environment. Experiments are also being conducted with the force-torque sensor and probe conveyed by the xArm robot. The on-arm tests are being used to develop the operational concepts for the SAMPLR payload mission.

Simulants. Various simulants have been used in the specialized penetrometer testing. The main simulant used for experiments is the Colorado School of Mines highland simulant, CSM-LHT-1 [3].

Data Analysis: The specialized penetrometer data are separated into the penetration and relaxation portions for analysis. Curves are fit to the penetration and relaxation data. The penetration curve is modeled using a second-order polynomial, and the relaxation curve is modeled using a Maxwell rheological model consisting of an external Hookean spring in parallel with two Maxwell arms comprised of a Hookean spring and a Newtonian dashpot in series. The fitted curve coefficients are used in the characterization of the sample surface.

Applications: The specialized penetrometer has been shown to be sensitive to ice content [4], so it can be used in prospecting for ice on the Moon. Another application of the specialized penetrometer is testing properties of engineered surfaces in-situ. For instance, the instrument can be used to evaluate a surface before and after compaction to ensure the intended surface density has been achieved.

Conclusions: The specialized penetrometer is a lightweight and relatively simple instrument that can provide a great deal of useful information about an in-situ surface. The instrument can aid in the characterization of a surface, evaluation of prepared and engineered surfaces, and in prospecting for volatiles. The specialized penetrometer technology will be demonstrated on a future CLPS mission where it will achieve space flight heritage status.

References: [1] Thrift B. C., et al. (2023) *Earth and Space 2022,* 137 - 149 [2] Dreyer C., et al. (2018) *Review of Scientific Instruments*, 89, 6, 064502. [3] Cannon K. (2023) *Planetary Simulant Database.* CSM-LHT-1. [4] Atkinson, J., et al. (2020) *Icarus*, 346, 113812.

New Basic Thermal Analysis Tool for Design and Results for Large Passive Greenhouses in LEO, Lunar, Mars.

D. V. Tompkins[1] and S. A. Ross[2], 'GrowMars .growmars2@gmail.com

Introduction:

The Carbon and Nitrogen cycles on Earth have considerable energy and biologically challenges as they also do in space. When sustaining life beyond Earth, the same considerations should be accounted for that can lead to an expanding loop proving essential resources. (1,2)

GrowMars is developing a family of greenhouse structures which allow for both algae and large plant growth on planetary surfaces and in orbit. Three instances within this family are a flat-panel system optimized for the surface of Mars, a vertically-oriented cylinder optimized for the lunar south pole, and a toroidal system for use as part of an orbital space station.

An approximate thermal analysis is carried out for each of these three systems. The core thermal solver is the Syrtis open-source code developed within Nexus Aurora. Modifications were made to allow for the different geometries and boundary conditions required.

Lunar system modeling

The Lunar system is modeled as a vertical cylinder located at 85°S. Thermal boundary conditions were obtained from SLS SPEC-159 Cross-Program Design Specification for Natural Environments [3] and HLS-UG-001 Lunar Thermal Analysis Guidebook [4].

A range of greenhouse cylinder diameters were modeled in hot and cold boundary conditions. Based on this analysis, it was determined that heat loss per square meter is relatively constant regardless of diameter.

Again, a full breakdown of numerical results is presented in the attached spreadsheet. For each of hot and cold environments, a "mean" temperature was used for representative conditions, and a "one sigma" temperature was used for a reasonable extreme - this encompasses 85% of the hottest noon temperatures and 85% of the coldest night temperatures. Table 2 lays out these conditions, along with an equilibrium temperature from the average of all habitats analysed. Property Cold "one sigma" Cold "mean" Hot "mean" Hot "one sigma" Ground temperature (K) 41 61 182 224 Solar insolation (W/m2), elevation angle 0 0 1360, 5° 1360, 5° Habitat equilibrium temperature (K) 33 50 338 340

Table 1: Cold day thermal balance, with and without active thermal control

Boundary condition	**Internal temperature**	**Heat loss or gain Diameter =4.5m Flux (W/m2)**	**Heat loss or gain Diameter =6.0m Flux (W/m2)**	**D=7.5m Flux (W/m2)**
Hot one sigma	308K, 35C	Gain 92	Gain 79	69
	298K, 25C	Gain 138	Gain 125	113
Hot mean	308K, 35C	Gain 45	Gain 33	23
	298K, 25C	Gain 90	Gain 78	66
Cold mean	278K, 5C	Loss 252	Loss 250	248
	298K, 25C	Loss 322	Loss 319	316
Cold one s		Loss 253	Loss 250	248
	298K, 25C	Loss 323	Loss 319	316

References:

[1] GrowMars Process for Expanding Oxygen, Food, Radiation, Manufacturing Material Production Rates D. V. Tompkins and A. C. Muscatello AIAA 2020-4153 Session: Transformative Technologies for Space Exploration II Published Online: 2Nov2020 https://doi.org/10.2514/6.2020-4153

[2] Architecture for a Farm in a Moon Village with In-Situ Materials for Infrastructure ARCHITECTURE FOR A FARM IN A MOON VILLAGE WITH IN-SITU MATERIALS FOR INFRASTRUCTURE. A. C. Muscatello, J. D. Burke, R. P. Mueller, N. J. Gelino, B. C. Buckles, and D. V. Tompkins.

[3] Cross-Program Design Specification for Natural Environments (DSNE) Revision https://ntrs.nasa.gov/citations/20200000867

[4] Human Landing System Lunar Thermal Analysis Guidebook.https://ntrs.nasa.gov/citations/2021001000

Captured Regolith Thermal Batteries for Lunar Night Survival.

N. W. Traeden[1] and H. J. Williams[1], [1]Honeybee Robotics, 2408 Lincoln Ave, Altadena, CA 91001, NWTraeden@honeybeerobotics.com

Introduction: In situ resource utilization has been proposed to decrease mass of a variety of elements needed to achieve Lunar Permanence, but many current architectures for overnight energy storage rely on materials brought exclusively from Earth such as batteries and fuel cells. Fuel cells are not infinitely scalable. Battery mass represents a large portion of mass for night surviving systems depending on existing technology, and batteries are a common cause for failure (up to 20%) [1]. Current radioisotope heating units are too low TRL for immediate integration, while other technologies like heating of phase change materials incur steep launch mass costs. A low mass, scalable, simple, readily-available alternative to existing night survival technology is necessary. We propose a new system using Lunar regolith to store and slowly release thermal energy to survive the Lunar night.

Lunar regolith in vacuum is a highly insulative material, with a heat transfer coefficient of under 1.5 × 10-4 W/cm K even when fully densified [2]. To make use of Lunar regolith as a thermal mass for storing heat, the concept of Lunar thermal wadis was put forward by Balasubramaniam et al [3]. This concept proposed the use of materials with even lower thermal conductivity than regolith and included regolith melting as a potential element. Issues with the thermal wadi concept include difficulty introducing heat to large amounts of regolith without massive support equipment.

Terrestrial thermal energy storage (TES) systems are regularly used with concentrated solar power plants to smooth output [4]. Some recently developed systems capture energy from renewables during peak production times to provide grid area heating [5]. Some of the simplest TES systems store heat in the form of sensible energy; in which they raise the temperature of a stored medium, like mineral oil or silica sand. This energy is later extracted using heat exchange systems.

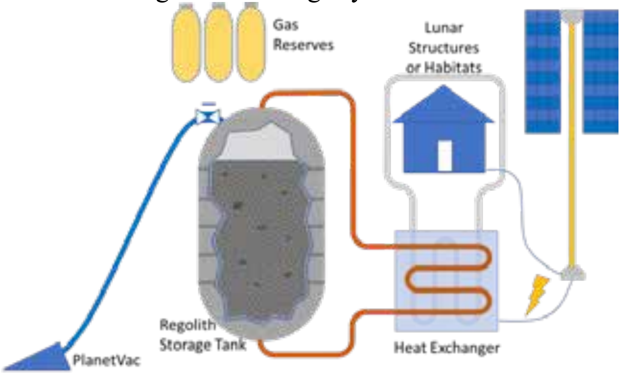


Figure 1: High level RAiNSS architecture

Honeybee has developed the Regolith Aided Night Survival System (RAiNSS), a new method, drawing on elements from these previously developed Lunar and terrestrial technologies: pumping heated gas in a closed system through a storage tank of collected Lunar regolith for thermal energy storage.

Honeybee Robotics has proven pneumatic stirring and transport of Lunar regolith to be an effective and well-established technique through the multiple CLPS missions [6]. RAiNSS holds gas in a tank and preheats it using thermoelectric heaters wrapped around the tank. The gas is introduced into the closed regolith-holding container in direct contact with the regolith, stirring and heating it. This alleviates the thermal conductivity issues associated with transferring large amounts of heat to lunar regolith. Pumps move gas between the container and tank, repeating the process to increase regolith temperature to just below melting. During periods of darkness, cooled gas is used to extract heat from the regolith thermal mass to provide thermal energy to Lunar structures or habitats. RAINSS is highly scalabe and potentially mobile, providing a night survival system for various Lunar vehicle architectures.

Conclusion: Using RAiNSS, we have created a system for night survival with high TRL, low political risk technology, ready for a technology demonstration mission within the next five years.

References:

[1] Bintoudi, Angelina D., et al. "Design of Space Microgrid for Manned Lunar Base: Spinning-in Terrestrial Technologies." 2019 *European Space Power Conference (ESPC)*. IEEE (2019)

[2] Vaniman, David, et al. "The lunar environment." *Lunar Sourcebook* (1991)

[3] Balasubramaniam, Ramaswamy, et al. "Analysis of solar-heated thermal wadis to support extended-duration lunar exploration." *Journal of thermophysics and heat transfer* 25.1 (2011)

[4] Kuravi, Sarada, et al. (2012). Thermal Energy Storage for Concentrating Solar Power Plants," Technology and Innovation. Journal of the National Academy of Inventors. 14.

[5] Eronen, Tommi, and Markku Ylönen. A System and a Method for Storing and Transfering Heat. WO 2020/183063 A1, 17 Sept. 2020, patents.google.com/patent/WO2020183063A1/en.

[6] Zacny, Kris, et al. "PlanetVac: pneumatic regolith sampling system." 2014 *IEEE Aerospace Conference*. IEEE (2014)

Development of an Ejector Driver Reactant PEM Fuel Cell System to Support Lunar Surface Power Operations.

R. Utz[1], R. Wynne[1], and C. Cox[1], [1]Teledyne Energy Systems, Inc., 10707 Gilroy Rd, Hunt Valley, MD 20131, (Contact: Rob.Utz@teledyne.com)

Introduction: Interest has grown in recent years for high energy power systems to support an increase in activity on the Moon, including a return of human presence targeted by the Artemis program. Batteries and solar panels have traditionally supplied power and energy storage in space applications with lower energy storage requirements. The need to extend mission duration on the lunar surface and survive the 14-day lunar night in most locations requires an increase in energy density that batteries and solar panels cannot achieve.

NASA has supported the development of technologies that may be able to meet the high energy density requirements in the lunar environment. Nuclear power sources have a proven track record terrestrially but are still in the early stages of development for lunar applications. Radioisotope power sources have been reliable performers for deep space probes and planetary rovers but may have restrictions upon use in manned missions due to radiation exposure. Regenerative fuel cell (RFC) systems can satisfy the high energy density requirements while not presenting compatibility challenges with human presence and are in the intermediate stages of technology readiness [1].

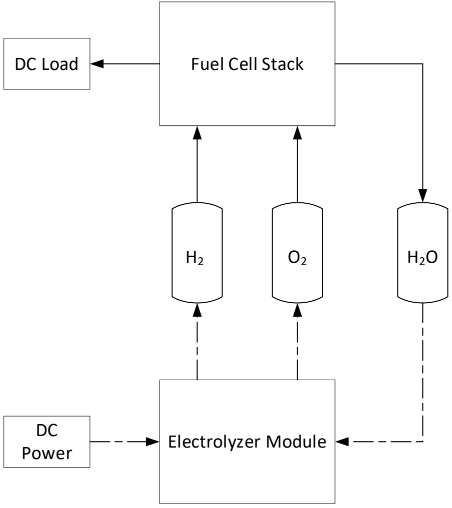


Figure 1: Regenerative Fuel Cell Schematic

Regenerative fuel cell systems have been studied as a potential power system concept that can provide many operational benefits to the user. RFCs are fuel cell power systems that are reversible, meaning that they can be operated both in fuel cell mode to produce power with reactant inputs and in electrolysis mode to produce reactants with power input (see Figure 1). When designed as a closed loop system, the reactants produced during electrolysis are kept in storage to be used later in fuel cell mode for power production. Conserving reactants through closed loop system design in RFCs enables long duration power system operation in a smaller package by eliminating the need to refuel.

Teledyne Energy Systems, Inc. (TESI) has developed the Ejector Driven Reactant (EDR) proton exchange membrane fuel cell (PEMFC) system as a solution for multiple applications with power demand ranging from 500 W to 8 kW. The EDR Fuel Cell System can serve as the fuel cell in a lunar RFC supporting human presence. The use of pure hydrogen and oxygen reactants with high efficiency membrane electrode assemblies has the potential for an order of magnitude energy density increase over batteries. Achieving high energy densities in space applications requires novel design concepts for the fuel cell stack bipolar plates and fuel cell balance of plant (BOP) components. The BOP design provides passive means of reactant flow control and water management integrated directly within the stack footprint with minimal parasitic power losses.

Teledyne Energy Systems has advanced the TRL of the EDR Fuel Cell System for space applications. A product water separator that can be directly integrated into the EDR system has been designed, analyzed, and tested. The water separator was experimentally shown to be capable of removing all product water generated by the stack in both lunar and zero gravity conditions on a parabolic flight. The water separator design will be integrated into an EDR Fuel Cell System to be launched on a suborbital flight in 2023. The EDR Fuel Cell System is anticipated to be ready for integration into a customer application to begin flight testing for use in a lunar environment by 2024.

References: [1] Jakupca, I.(2019) *DOE H2 AMR, 90,* IA-014.

Field Testing Lunar Thermal Cone Penetrometer and Ground Penetrating Radar. P.J. van Susante[1], G. Johnson[1], B.D. Wiegand[1], T. Wavrunek[1], M.C. Guadagno[1], C. Kaminsky[1], J. Allen[1], T.C. Eisele[1], T. Scarlett[1], R. Alger[1], K.A. Zacny[2], S. O'Brien[2], B. Yen[2], [1]Michigan Technological University, 1400 Townsend Dr., Houghton, MI 49931, [2]Honeybee Robotics, 2408 Lincoln Avenue, Altadena, CA 91001. (Contact: pjvansus@mtu.edu)

Introduction: As part of the sustainable return to the lunar surface, using the local resources is planned. Particularly ice that can be found in the lunar permanently shade regions to manufacture rocket propellant, is of interest. Before mining and finalizing excavator and processing plant design can be completed, the location, quantity, distribution, and type of the volatiles needs to be determined as well as the geotechnical properties of the material to excavate/process. Michigan Technological University's (MTU) Planetary Surface Technology Development Lab (PSTDL) has developed a Percussive Hot Cone Penetrometer (PHCP) which, in combination with ground penetrating radar (GPR), is designed to determine geotechnical properties and identify the volatiles down to 1m depth. A field test in a created trench filled with lunar regolith simulant and icy layers was performed in winter 2023 as an operational test. Preliminary data will be presented in this presentation. This work was supported by a Lunar Surface Technology Research (LuSTR) grant from NASA's Space Technology Research Grants Program.

Percussive Hot Cone Penetrometer: The core capability to measure the geotechnical properties and identify and quantify the volatiles present is as system consisting of an instrumented cone penetrometer. The cone has been instrumented with a heater, thermocouples and a load cell and the rod has been instrumented with strain gauges. The rod is attached to a modified TRIDENT percussive z-stage manufactured by Honeybee Robotics. This setup allows measurement of impact forces, tip resistance forces, vertical displacement to determine geotechnical properties. Every 10 cm, the cone penetrometer will stop to activate the heater, the thermocouples will then meausure the thermal variation over time and from the thermal profile, the type and quantity of volatiles present can be determined. A data set of thermal profiles of several cryogenic volatiles in lunar regolith under vacuum conditions is being created to facilitate the identification of the volatiles.

Ground Penetrating Radar: Detecting layering and lateral variation and distribution of ice and rocks in between the cone penetrometer locations is done by GPR. For our purpose a commercial off the shelf (CoTS) GPR unit from Sensors and Software is used. Both a 500 MHz and 1000 MHz antenna and receiver is used due to the 1 m depth of interest and resolution needed.

Field Rover: Both the PHCP and the two GPR antennas are mounted on PSTDL's fieldrover, HOPLITE.

Test Site and Trench: The 6m long by 1.5m wide and 1.25m deep trench was built at the 900 acre Keweenaw Research Center proving grounds facility of MTU. The trench was filled with 25,000 kg of lunar regolith simulant (MTU-LHT-1A) and layers of different depth, density and ice content were created. Two different cross sections were created in two zones of the trench.

Simulant and Ice Layering: MTU-LHT-1A is a simulant made from mixing Anorthite Greenspar 90 and Greenspar 250 with crushed basaltic scoria to match Apollo lunar highland particle size distribution. Ice is mixed in when everything is below freezing using a cold/frozen cement mixer truck. The cement truck deposits the mixture into the trench where it is compacted to the desired relative density. The layers created vary in density from 1.5 g/cc to 1.8 g/cc and the added ice content varied from 0% (dry) to 6%. The layer thickness varied from 20 cm dry toplayer on top of icy underlayers to a uniform 6% ice containing mixture.

Test Procedure: Once a freezing weather prediction of at least 10 days is confirmed, the trench is prepared with the simulant and icy layers. The field rover is lifted in place by a forklift. The fieldrover drives forward while using GPR. Stops to perform the PHCP test down to 1m depth collecting geotechnical and thermal data. Retracts, drives to the next location while collecting GPR data and repeats several times over the two zones. After the first test series is complete, the testbed is emptied into superbags and mixed with additional ice for higher ice content testing. New layers are made and another set of data is collected. All regolith simulant will be dried over several months in PSTDL's 40ft drying container at 1000 kg per batch.

Results: Layering and Ice is detected. Details and results will be presented at the conference.

Thermal Profiling to Identify and Quantify Cryogenic Volatiles in Lunar Simulant under Vacuum Conditions.

P.J. van Susante[1], G. Johnson[1], T. Wavrunek[1], E. Zimmerman[1], M. Krause[1], J. Allen[1], T.C. Eisele[1], T. Scarlett[1], A. Rajan[1], [1]Michigan Technological University, 1400 Townsend Dr., Houghton, MI 49931. (Contact: pjvansus@mtu.edu)

Introduction: As part of the sustainable return to the lunar surface, using the local resources is planned. Particularly ice that can be found in the lunar permanently shade regions to manufacture rocket propellant, is of interest. Before mining and finalizing excavator and processing plant design can be completed, the location, quantity, distribution, and type of the volatiles needs to be determined as well as the geotechnical properties of the material to excavate/process. Michigan Technological University's (MTU) Planetary Surface Technology Development Lab (PSTDL) has developed a Percussive Hot Cone Penetrometer (PHCP) which, in combination with ground penetrating radar (GPR), is designed to determine geotechnical properties and identify the volatiles down to 1m depth. Thermal profiles of several volatiles in various concentrations in regolith were measured under vacuum and cryogenic LN2 cooled conditions. Preliminary data will be presented. This work was supported by a Lunar Surface Technology Research (LuSTR) grant from NASA's Space Technology Research Grants Program.

Atmospheric and Vacuum Testing: Mixtures of varying concentration of water ice and regolith were initially tested with a heater and thermocouples spread in the regolith to measure thermal conductivity and other properties of the mixtures. Varying relative densities were used to quantify the effect on the properties. After some testing in vacuum conditions it was found that air is trapped in the void space between the particles due to the regolith simulant's low permeability (just in the clay range) which affects measurements in vacuum as well as it leading to gases becoming trapped and leading to changes in triple point compared to the vacuum level in the chamber. For the other volatiles cryo testing under vacuum conditions is needed, and a vibratory setup was created that would vibrate the regolith and icy volatile mixture so that most trapped air would be either frozen or escape.

Test Setup: 2 kg Cryocooled regolith is mixed with cryocooled volatile snow and transferred to the LN2 cooled vacuum vessel that contains a heater and thermocouples at fixed locations. Once filled and sealed, the vacuum pump is engaged while vibrating the vacuum vessel to release any trapped air in between the particles as well as create compaction. The final relative density is estimated and the test can start. Once final vacuum levels have been achieved, the heater is turned on and thermocouple measurements are taken until no more changes occur. The test setup is then brought back to atmospheric pressure and allowed to heat up and safely vent into the fumehood. The system is reset and the next test is performed.

Regolith Simulant and Volatiles Used: The regolith simulant is 2 kg of MTU-LHT-1A consisting of Anorthite (Greenspar 90 and 250) and crushed basaltic scoria with a particle size distribution matching the Apollo highland samples. Volatiles used are: Carbon-Dioxide, Methane, Ethylene, Methanol and Sulfur-Dioxide. These were chosen for their relative safety for testing and presence in the lunar regolith. Concentrations of 1-6% are tested.

Example Data: Data gathered will be presented for example volatile cases, similar to the data shown for an atmospheric case of frozen regolith mixed with ice.

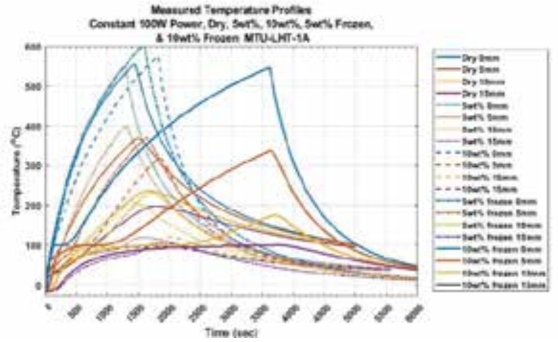


Figure 1: An example plot of the data gathered for lunar simulant at 100W power heating level for different water percentages (dry, 5% and 10% wet and 5% frozen) and the measured temperature at a distance of 0, 5, 10 and 15mm from the heater showing phase changes and clear distinctions between percentages water or ice content.

Results: Thermal profiling allows for identification of volatiles in cryogenic regolith under vacuum conditions. Details and preliminary results will be presented at the conference.

Efficient Truss Structures from Regolith Glass. R. T. Wainner,[1] C. M. Hessel,[1] B. E. Nunan,[1] W. J. Kessler[1], T. Guenther,[2] R. N. White,[2] and M. Stern.[3] [1]Physical Sciences Inc., 20 New England Business Center, Andover, MA 01810. [2]Lucideon M+P, 2190 Technology Drive, Schenectaady, NY 12308. [3]Evenline Inc., 336 Mulberry Street, Rochester, NY 14620.
(Contact: wainner@psicorp.com)

Introduction: Physical Sciences Inc. (PSI) and collaborators are developing a methodology for the production of robust and mass-efficient truss-based structures from melted and reformed regolith for space construction applications. The effort includes; 1) the design of space-worthy hardware for producing the regolith glass primary building components (rods and nodes); and 2) the design of process by which the components may be assembled securely and accurately into truss building blocks to be utilized in larger constructions.

The current project targets an end goal truss design of 5m length with triangular cross-section and aspect ratio ~50. Length and straightness target accuracy metrics of $1\text{x}10^{-4}$m and 1.3mm/m lend themselves to the construction of large orbital structures with high precision. Similar straightness requirements are imposed on the glass rods that make up the assembly. Truss strength objectives and strength of the regolith glass material dictates the allowable fineness of the rods that comprise it. However, varying lunar or orbital construction applications can call for different strength and shape requirements. The method will be flexible for producing parts and building blocks of different character.

This paper describes summary results from the DARPA-funded project that is still underway and will produce as an end goal objective one or more exemplar trusses of 2m length, constructed of regolith simulant glass rods that are welded together to produce the (essentially node-free) construction. Molded regolith glass nodes are still anticipated, however, to enable the joining of multiple trusses together at their ends.

Material Development/Analysis: The project has entailed a deep dive into regolith (simulant) intrinsic properties, as well as produced glass product-oriented properties. One example of intermediate properties is illustrated in **Figure 1**. Here, 4-point flexural testing of drawn regolith rod stock has helped identify allowable anneal recipes and reveals a robust modulus of elasticity for the glass that is near 85 GPa (higher than borosilicate).

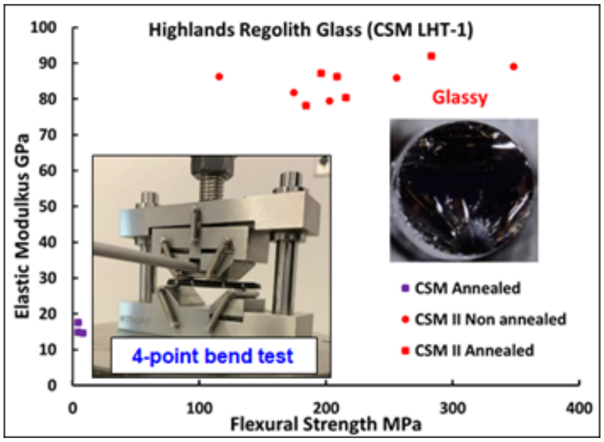


Figure 1. 4-point bend testing of regolith rod specimens. Inset pictures show the test apparatus with regolith rod & deflectometer in place, and cross-section of a sample at its failure surface.

Truss Design, Build, & Test: In structural efforts, regolith glass strength data has helped inform an overall design to the truss for a mass-efficient design that employs producible (5mm) diameter rod stock. In addition, exploration of different rod-to-rod joining methods was explored and the glass welding approach was settled on as most promising (viable and mass-efficient). Machinery for the production of regolith 'cane' (rod stock) is still under development, but assembly methods are being refind on conventional (5mm dia.) borosilicate glass rods. This includes weld methodology and jigging for assembly. Figure 2 illustrates a welded 2m truss of borosilicate glass, as well as the jig employed to allow its precision construction.

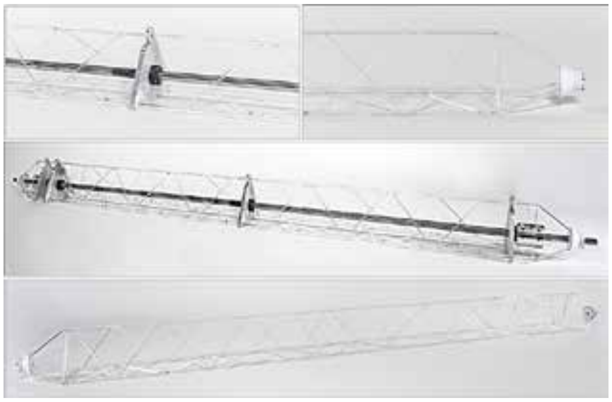


Figure 2. Photographs of the prototype 2m welded glass truss, buiit in borosilicate, with and without assembly jig in place.

Solar Concentrator System for Lunar ISRU Applications. R. T. Wainner,[1] K. L. Galbally-Kinney,[1] T. Nakamura, and W. J. Kessler[1], [1]Physical Sciences Inc., 20 New England Business Center, Andover, MA 01810. [what is Takashi's appropriate contact info?]
(Contact: wainner@psicorp.com)

Introduction: Physical Sciences Inc. (PSI) has developed a space-compatible concentrated solar power (CSP) optical waveguide system for lunar In-Situ Resource Utilization (ISRU) applications. In this system, solar radiation that is collected with a large mirror is focused into a novel optical waveguide (OW) transmission cable made of low loss optical fibers. The OW transmission cable directs the concentrated solar radiation to applications needing high intensity energy including: 1) Oxygen production from thermochemical processing of lunar regolith; 2) Lunar regolith sintering/melting for surface stabilization; and 3) Manufacturing of building blocks for in-situ lunar construction. Key features of the technology under development are:

1. Highly concentrated solar radiation (1's-10's MW/m^2) can be transmitted via the flexible OW transmission line directly to the thermal receiver for oxygen production from lunar regolith.
2. Power scale-up can be achieved by incremental increase of the number of concentrator units.
3. The system can be autonomous, stationary or mobile, and transported and deployed on the lunar surface.
4. The system can be applied to multiple lunar ISRU processes.

This paper describes summary results from the design, build, and preliminary testing of a prototype OW designed to serve the requirements of NASA's Carbothermal Reactor Demonstration (CaRD) test project. This test campaign aims to combine the PSI waveguide with NASA-built solar concentrator, and a prototype oxygen-from-regolith (O2FR) reactor from Sierra Space. Different tests will employ thermal vacuum chamber, laser illumination, solar illumination, and waveguide / delivery optic configurations.

Waveguide Development: Building on PSI technology that was developed and tested in 2010,[1] the development efforts summarized here focused on: 1) improved power throughput; and 2) more versatile power delivery, with configurable standoff and focal intensity. **Figure 1** illustrates the major components of the concentrated solar power concept, while **Figure 2** depicts the constructed prototype OW cable.

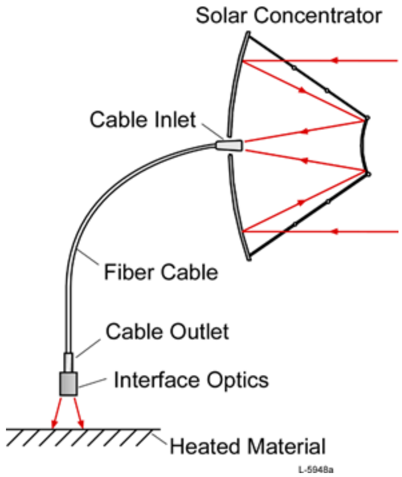


Figure 1. Schematic representation of an integrated fiber-coupled concentrated solar relay system.

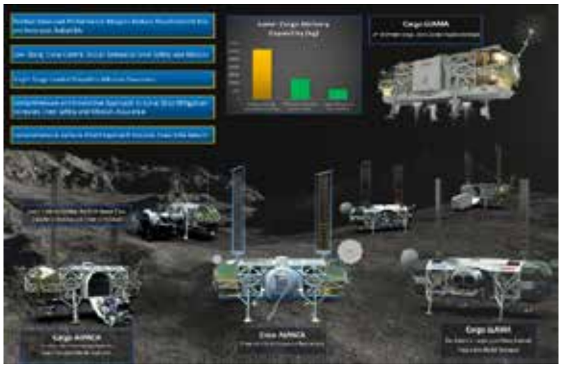
Figure 2. Photographs of the prototype OW cable.

References:

[1] Nakamura, T., Smith, B.K. and Irvin, B.R. (2015) *J Aero Eng (ASCE), 28, 1.*

Dynetics Human Landing System: Lunar System Utility Vehicle. J. Blalock[1], T. Theno[1], and M. D. Watson[1] [1]Dynetics, Space Division, Human Landing System, 355 Quality Circle NW, Huntsville, AL 35806. (Contact: michael.d.watson@dynetics.com)

Introduction: Dynetics Human Landing System (DHLS) provides a high utility lunar servicing system for NASA and commercial users needing agile and flexible transportation solutions. The DHLS provides a vehicle with a tremendous amount of transportation utility. On Earth, we do not always need to travel on large ocean transports, often we need more accessible travel methods. The DHLS configurations provide this flexible solution. The landers have 3 configurations: Crew Autonomous Logistics Platform for All-Moon Cargo Access (ALPACA), Cargo ALPACA, and Cargo Lunar Logistics for All Moon Access (LLAMA). The Crew ALPACA provides transport of upto 4 crew members with a small access height to the surface. The Cargo landers have the same basic subsystems with the Crew Module replaced by the cargo. These landers have a small surface foot print and accommodate a variety of surface landing conditions to place crew or cargo exactly where they need to be. This minimizes surface transportation distance and time, simplying surface transportation solutions. The landers can serve as a taxi between surface sites, transporting crew or cargo quickly and easily across rugged terrain and placing them at the desired location at the next site. For crew support, the Crew ALPACA can also function as an ambulance, med evacing injured or sick crewmembers back to the Gateway or Earth return vehicles such as the Orion or other commercial return vehicles. Cargo landers provide numerous cargo support options. The cargo landers can mate with the cargo containers in NRHO to bring them to the lunar surface. Multiple cargo transport attachements are possible to be developed as mission kits. Cargo elements can be self contained or transported in a portable payload module (PPM). The PPM provides support services and the cargo elements can remain supported for short stays during their initiation. In addition, a cargo lander can remain on the surface as an infrastructure element providing electrical power and communication servces to cargo elements such as habitats. The PPM can also garage portable cargo items either as a separate element remaining on the surface or as part of the lander infrastructure element. A mission kit can be developed or provided as part of the cargo for the LLAMA to deliver cargo as a sky crane, enabling access to difficult to reach locations. This mission kit would include shielding from the plumes during lowering of the cargo. For large cargo items such as multis-story habitats or large astronomical telescopes, cargo lander tandem operations can be developed for the lander to fly in a team formation to deliver cargo 5 – 10 m in diamenter and 10’s m long.



LunaGrid; Considerations for Developing an Expandable & Distributed Lunar Power Grid

E.B. Williams, T. Arbuckle, J. Landreneau, Astrobotic (1016 N. Lincoln Avenue, Pittsburgh, PA 15233)

Introduction: NASA’s goal is to help create a thriving lunar economy. A lunar power grid is foundational to that objective and would support the Artemis missions. By providing power as a service on the lunar surface it will be possible to substantially reduce the mass of surface equipment and the expenses associated with delivering and operating them. A prerequisite is the use of technology which provides a path to surface operation of the first nodes within 3 to 5 years to support mission roadmaps and provides power to customers at ≤120Vdc. The following sections describe the basis for several key characteristics of our LunaGrid service which can satisfy both near and long term goals.

State of Technology: The use of transmission cables with simple metallic conductors represents the strategy with the lowest program risk for lunar power transfer [1]. Transmission cables also have an existing supply chain to leverage. Several recent publications have shown that AC transmission over long distances is the more feasible and reliable solution compared to DC transmission [1, 2]. The use of radiation tolerant transformers to achieve the transmission voltage provides a more reliable solution compared to combining derated silicon or GaN converters in series. Existing AC microgrid controllers and algorithms, specifically Droop Control, provides a robust solution for maintaining grid stability without the need for direct communications between nodes for primary grid control (i.e. decentralized). This also provides an existing knowledge base and the benefit of experience with managing fault scenarios experienced in microgrid and “off the grid” applications on earth.

The Micro-grid Definition and Interface Converter for Planetary Surfaces (MIPS) team at NASA’s Glenn Research Center (GRC) have recommended high voltage transmission at 3kVac. To enable this solution, they have developed the Universal Modular Interface Converter (UMIC) which provides bi-directional conversion between 120Vdc and 3kVac using modular components [3].

Expansion of the Grid: The grid architecture and infrastructure planning is based on progressively adding more nodes over time but without knowledge of the exact geographic locations and power demand needed in the future. NASA’s Strategic Framework seeks to develop large scale power transmission (>100’s km) using lunar resources. Any near-term solution being developed must advance the electronics toward that objective but also create a physical and spatial layout which can accommodate that evolution. Designers must consider the obstruction which these in situ surface cables will create. Minimally insulated cables provide a very low kg/km and also establish the paths and accommodations that will be needed for in situ cables while providing efficient traffic paths, similar to terrestrial roads and power lines.

The electronics and transmission system utilize components and sub-systems which are modular, such as the UMIC. In this context modular is defined as a component or subsystem that provides a fixed amount of power, but when combined can provide the sum of their individual powers. Converters, transformers, and cables will be modular. To maintain reliability these modular components are configured such that if one fails, only the power from that component is lost.

Each distributed generation node within the grid will have its own energy storage device so that grid stabilizing storage increases as more generation capacity is added. Like the energy requirements of a particular application on Earth, risk tolerance and criticality of the application will dictate the appropriate independent backup storage and generation needs. Additional energy storage could be in a specific node or within the user's system, much like how hospitals have emergency power sources.

Finally, the electrical architecture is configured to prioritize conversion efficiency to the grid. As the grid and lunar economy grow, multiple distributed generation nodes (VSATs, FSPs) will be used to provide power to large power consumers or locations. A large user requires power supplied from multiple nodes. However, if this is not the case, alternative configurations are possible since the system is modular.

References:

[1] Barth C. and Pike D. (2022) Lunar Power Transmission for Fission Surface Power. Nuclear and Emerging Technologies for Space 2022

[2] Csank J., Thomas G., Granger M., Gardner B. (2022) Powering the Moon: From Artemis Technology Demonstrations to a Lunar Economy. Nuclear and Emerging Technologies for Space 2022

[3] DeMinico M., Csank J. (2022) FY22 Micro-grid Definition and Interface Converter for Planetary Surfaces (MIPS) Annual Review Presentation. STMD Game Changing Development Program 09/12/2022

A Simulated Lunar Electrical Grid Using Terrestrial Microgrid Modeling Methods.

H. J. Williams[1], [1]Honeybee Robotics, 2408 Lincoln Ave, Altadena, CA 91001 (Contact: hjwilliams@honeybeerobotics.com)

Introduction: Consistent electrical power availability is one of the key challenges to sustained human presence and space resource utilization activities [1]. With sufficient power, surviving the lunar night and working in the permanently shadowed regions are feasible. Solar power is an enabling resource anywhere at the Lunar surface, but particularly so at the Lunar Poles where there are persistently lit regions with up to 91% yearly illumination [2]. Connecting a series of solar arrays over several kilometers could allow for the creation of an electrical grid, offering stable and permanent power when one array powers the other as the light shifts location through the Lunar day.

Background: Apollo mission architecture was driven by the goal of beating the Soviets to land a human on the Lunar surface. This overarching goal lead to requirements that heavily emphasized speed, safety, and reliability, and de-emphasized mission longevity and power availability beyond the most restrictive needs of the mission [3]. These constraints precluded solar power due to timing constraints from the Lunar month and precluded a nuclear reactor due to TRL and safety. However, all large, high reliability systems and low cost planetary surface missions have used rechargeable power sources. The International Space Station runs on a combination of rechargable batteries and solar panels. The Russian Lunokhod rovers and the Chinese YuTu rovers both were solar powered with rechargeable batteries [4] and radioisotope heaters. Over several decades and different countries, when longevity of power provision is the driving factor, rechargeable batteries and solar panels are the method of choice.

The Lunar Grid: The building blocks of an electrical grid for the Lunar surface have been in development for several years. This grid will be a fundamentally enabling infrastructure for long-duration human missions, robotic science missions, and the build-up of several space resource utilization value chains. Through NASA Space Technology Mission Directorate programs such as Lunar Vertical Solar Array Technology (LVSAT), Small Business Innovation Research (SBIR), and Tipping Point, NASA has funded the development of several building blocks for a modular electrical grid including solar arrays, nuclear fission reactors, regenerative fuel cells, power beaming technologies, tethers, and dust tolerant electrical connectors. These building block technologies have been developed to various TRLs and most remain untested in the Lunar environment.

Though the Lunar grid has been proposed as an enabling resource for years, designs have been mostly architectural and built around specific missions without long-view planning. During this time, Lunar grid design work was centered on generation and transmission elements, used static assumed loads, and was performed under an aerospace-centric development model. Though these studies have appropriate assumptions and foci for general architecture, they have lacked a key element used in all terrestrial micro-grid construction projects: a plan for grid element selection and placement incorporating a time-dependent load model and a location-dependent voltage model.

To remedy this issue, Honeybee has been developing a Lunar grid simulation based on tools created for modeling terrestrial micro-grids. The aim of this work is to **develop a framework for realistically investigating the challenges of building a Lunar electrical grid**. This framework will decrease the amount of supposition and reliance on low TRL technology for Lunar mission planning by the community. This includes NASA civil servants making general mission plans and technology taxonomies, payload developers who are developing these mission-critical technologies and are also potential end users of Lunar electrical power, space resource utilization practitioners developing technology that must scale to available power, and private firms capable of building a Lunar electrical grid, determining the necessary conditions for market entry.

References:

[1] Sanders et al. "Results from the NASA capability roadmap team for in-situ resource utilization (ISRU)." (2005).

[2] Kruijff, Michiel. "Peaks of Eternal Light on the Lunar South Pole: How They Were Found and What They Look Like." Exploration and Utilisation of the Moon. Vol. 462. 2000.

[3] Bell III, David, and Fulton M. Plauché. "Apollo experience report: Power generation system." (1973).

[4] Kassel, Simon. Lunokhod-1 Soviet lunar surface vehicle. RAND CORP SANTA MONICA CA, 1971.

Lunar Base Planning: Driving Consensus on Development Logics Informing a Morphological Approach to Lunar Infrastructure. M. Yashar[1], E. Jensen[1], and J. Ballard[1], [1]ICON Technology Inc, 220 E St Elmo Road, Austin, Texas 78745 (Contact: melodie@iconbuild.com)

Introduction: Project Olympus is ICON's multi-year initiative to develop an autonomous, large-scale construction system capable of manufacturing horizontal and vertical structures on the Moon and eventually Mars. ICON is developing Project Olympus in support of the Moon-to-Mars Planetary Autonomous Construction Technology (MMPACT) project to address the lunar surface construction thrust area of the Lunar Surface Innovation Initiative (LSII). The goal of the MMPACT project is to develop, deliver, and demonstrate on-demand capabilities to protect astronauts and create infrastructure on the lunar surface via construction of landing pads, habitats, shelters, roadways, berms and blast shields using lunar regolith-based materials [1]. As a part of the MMPACT program, ICON and NASA are evaluating multiple additive construction technologies, materials, and construction element forms.

Large-scale additive construction is uniquely suited for both earth and space applications in that it enables construction of many types and varieties of structures on-demand and in variable settings using local materials [2]. Terrestrially, ICON is not only as a service provider and design-builder for development-scale automated construction projects, but is also actively engaged in master planning and urban-scale development for the communities it builds. Large scale automated additive construction is a disruptive technology capable of delivering housing and other building typologies at production scales never before witnessed in traditional construction practices [3]. Automated construction technologies enable the rapid re-development and creation of new communities and urban centers, while also enabling opportunities for ground-up solutions addressing warranted social, ecological, and economic solutions for the respective communities. Adopting similar data-driven approaches to urban and master planning at the Lunar south pole may enable new opportunities and added value for infrastructural development.

In this presentation we outline the need for Lunar base planning development logics enabling a morphological approach to infrastructure development and strategic expansion at key landing sites at the Lunar south pole. Anticipating that key infrastructural elements such as landing pads, roads, and utilities such as communication and power lines will be shared by multiple Lunar surface actors, we encourage the development of shared requirements for such infrastructure elements, and propose the creation of knowledge communities within LSIC to actively engage and contribute to the development of said requirements and parameters at an urban scale. Parameters and requirements might include topics or research areas such as program and activity adjacency studies, safety keep out zones, topographical and geological surface requirements for infrastructural development, protected areas for science and research, and more.

A parametric development model and framework for Lunar infrastructural development will enable and account for rapidly changing needs and interests from science, commercial, and governmental organizations and institutions. In contrast to historical examples of static or fixed Lunar master plans, the ICON team proposes and develops a development logic for emerging morphologies of Lunar base planning. A parametric and data-driven framework may enable preemptive solutions at the infrastructural scale that account for, recognize, and ameliorate the needs and interests of multiple surface construction and development stakeholders in ways that are informed, intelligent, and anticipatory to future growth and development at an urban scale.

Figure (above): Concept for landing pad construction using Olympus construction.

[1] Clinton Jr., R. G., Edmunson, J. E., Effinger, M. E., Fiske, M. R., Ballard, J., Jensen, E., Yashar, M., Ciardullo, C., Morris, M., Pailes-Friedman, R., Moon to Mars Planetary Autonomous Construction Technologies (MMPACT), ASCEND, Planetary Construction technologies, November 8-10, 2021.
[2] Clinton Jr., R. G., Edmunson, J. E., Effinger, M. E., Fiske, M. R., Ballard, J., Jensen, E., Yashar, M., Ciardullo, C., Morris, M., Pailes-Friedman, R., H. Shulman, Q. Otte. NASA's Moon-to-Mars Planetary Autonomous Construction Technology Project: Overview and Status, IAC-22,C2,5,x6814. Paris, France, 18-22 September 2022.
[3] Fiske, et al., "The Disruptive Technology That is Additive Construction: System Development Lessons Learned for Terrestrial and Planetary Applications," 2018 AIAA SPACE and Astronautics Forum and

Investigation on heat transfer process of solar-sintered regolith for lunar ISRU program

Y. K. Zhang[1], G. A. Brooks[2], M. A. Rhamdhani[3], M. Shaw[4], and C. S. Guo[5]
[1]Swinburne University of Technology, yuankunzhang@swin.edu.au, [2]Swinburne University of Technology, gbrooks@swin.edu.au, [3]Swinburne University of Technology, arhamdhani@swin.edu.au, [4]Swinburne University of Technology, Matt.Shaw@CSIRO.au, [5]Shandong University, Weihai, guo@sdu.edu.au.
(Contact: yuankunzhang@swin.edu.au)

Introduction: Thermophysical property prediction of sintered lunar regolith plays a crucial role in developing extraterrestrial thermal processing and construction techniques for In-situ Resource Utilization (ISRU) projects on the moon [1-2]. Most existing literature have been focused on the Effective Thermal Conductivity (ETC) prediction of packed lunar regolith without considering the sintering mechanism [3-5]. This research developed a mechanistic ETC model of sintered lunar regolith. The Monte-Carlo method was applied to simulate the thermal neck resistance between multi-scaled particles, while the irregular particle geometry was characterized by shape factors. The presented model was validated using measured ETC and specific surface area of fabricated lunar simulant samples with various granularities sintered under air, Argon, and low vacuum (10^{-8} atm). Furthermore, the heat transfer process within solar-sintered LMS-1 bed was simulated coupled with the ETC model. Transient behaviors of microstructure, thermal conductivity and temperature profile during solar heating were simulated by synergistic computing. A good agreement (RMSE=5.6%) was observed between the simulated and measured temperatures compared to the no-sintered case (RMSE=12.5%). An optimal sintered depth of 26 mm was obtained with a special-designed particle size distribution (PSD) arrangement based on the modeling, indicating an improvement of 45% compared to the original PSD.

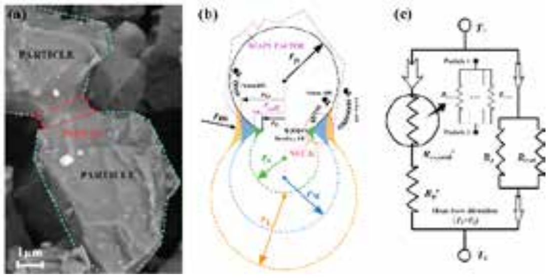


Figure 1. ETC model of sintered lunar regolith

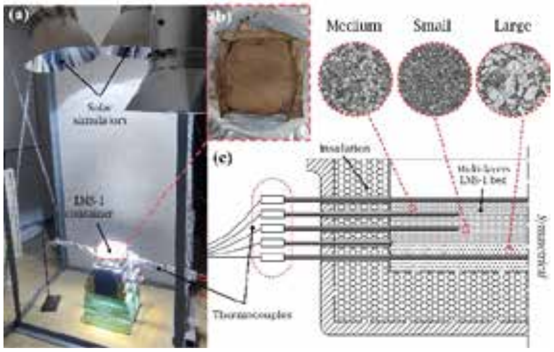


Figure 2. Solar sintering system with vertical mounted solar simulators.

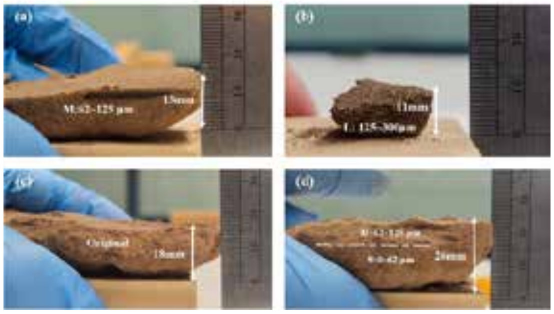


Figure 3. Optimization of solar-sintered regolith layer.

References:

[1] Shaw, M., et al. (2022) *Mineral MINER PROCESS EXTR. M.*, *43*(7), 865-891. [2] Isachenkov, M., et al. (2022) *Adv. Space Res.* [3] Woods, R., et al. (2019) A Model for the Thermophysical Properties of Lunar Regolith at Low Temperatures. *J. Geophys. Res. Planets*, 124 (7), 1989-2011. [4] Sakatani, N., et al. (2017) *AIP Adv., 7* (1). [5] Schreiner, S. S. et al. (2016) *Adv. Space Res.*, 57(5), 1209-1222.