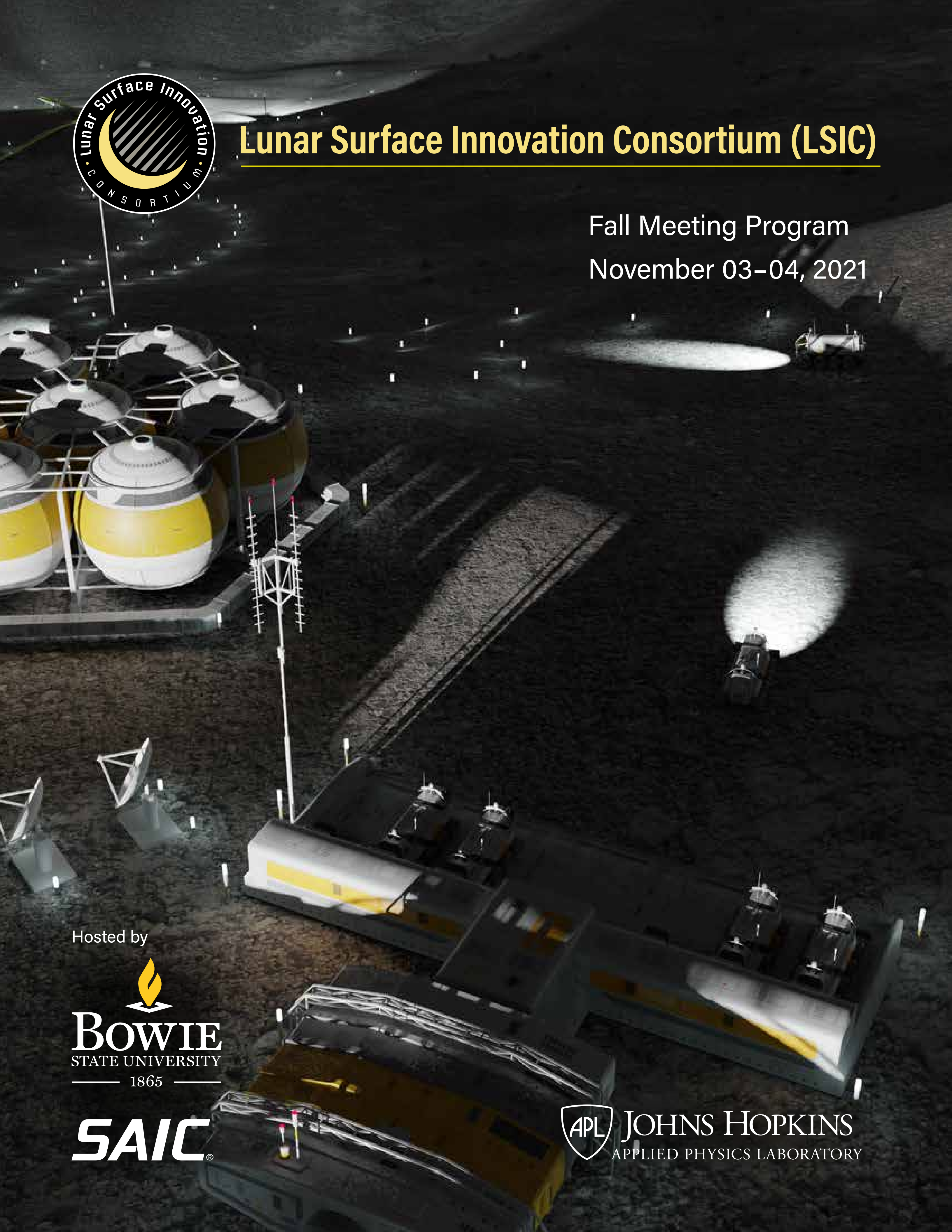
Lunar Surface Innovation Consortium (LSIC)

Fall Meeting Program

November 03–04, 2021



Hosted by

Bowie State University 1865

SAIC

Johns Hopkins Applied Physics Laboratory

Technical Organizing Committee

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Sarah Withee, LSIC, JHUAPL
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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 APL LSIC website for further information: http://lsic.jhuapl.edu

Lunar Surface Innovation Consortium (LSIC)
Fall Meeting Draft Agenda

All times Eastern
November 3rd-4th, 2021

Day 1 – Wednesday, November 3rd, 2021

9:30	*Coffee & Networking in Person and in GatherTown*	
10:00	Welcome and Introduction to Bowie State	**Dr. Aminta H. Breaux**, President Bowie State University **The Honorable Angela D. Alsobrooks**, County Executive Prince George's County, Maryland
10:30	A Message from NASA Administration	**Dr. Pamela Melroy**, Deputy Administrator, NASA
10:35	Welcome from APL	**Dr. Jason Kalirai,** Mission Area Executive, Johns Hopkins Applied Physics Laboratory (APL)
10:40	NASA Space Tech Update	**Jim Reuter**, Associate Administrator for Space Technology. NASA
11:10	*Break*	
11:25	LSIC Update	**Dr. Rachel Klima**, LSIC Director, Johns Hopkins Applied Physics Laboratory (APL)
11:45	Bowie State University Feature	**Dr. Anika A. Bissahoyo,** Assistant Vice President for Research, Bowie State University **Mark J. Fuerst,** Senior Program Manager, SAIC
12:05	Next Generation Lunar Scientists and Engineers (NGLSE)	**Amanda Stadermann,** NGLSE, University of Arizona
12:20	Lunar Base Conceptual Design	**CIRCUIT Interns**, LSII/APL
12:30	*Lunch Break – networking time in GatherTown, lunch, tours, and networking in person*	
1:30	Supply and Demand: Surviving the Lunar Night	**Kevin Somervill**, NASA
1:45	**Panel:** Investing in Cutting-Edge Technology: Building the Space Economy	**Moderator: Dr. Joshua Cahill,** APL **Candice Matthews Brackeen**, Lightship Capital **Michael Mealling**, Starbridge Venture Capital **Curtis Rodgers**, Brick and Mortar Ventures **Josephine Millward**, Seraphim Capital
2:35	*Break*	
2:45	**Panel:** Fostering Innovation In Industry and Academia	**Moderator: A.J. Coleman,** SAIC **Brett Lindenfeld**, Motiv Space **Dr. Angel Abbud-Madrid**, Colorado School of Mines **Lt Col Rock McMillan,** SPACEWERX
3:35	Lightning Talks	
4:15	Poster Session and Networking	
6:00	*Adjourn for the Day*	

Lunar Surface Innovation Consortium (LSIC)
Fall Meeting Draft Agenda

All times Eastern
November 3rd-4th, 2021

Day 2 – Thursday, November 4th, 2021

10:00	*Coffee & Networking in Person and in GatherTown*	
10:30	Welcome and Introduction	**Niki Werkheiser,** Director, Technology Maturation**,** NASA
10:40	Autonomous Operations on Earth	**Dr. Cara E. LaPointe,** Institute for Assured Autonomy, Johns Hopkins University
11:00	Introduction to NASA Robotics Roadmap and Investments	**Dr. Terry Fong**, Director of Intelligent Robotics NASA Ames
11:20	*Break*	
11:30	**Panel**: Robotic Flight Demonstrations	**Moderator:** Dr. Jamie Porter, APL **Dr. Danette Allen,** NASA Deputy for Robotics & Autonomy **Jason Schuler,** ISRU Pilot Excavator, NASA Project Manager **Daniel Andrews**, VIPER, NASA Project Manager **Dan Hendricksen**, CubeRover, Astrobotic **Matt Atwell**, Deployable Hopper, Intuitive Machines
12:20	*Lunch Break – networking time in GatherTown, lunch, tours, and networking in person*	
1:20	**Panel:** Robotics and Autonomy – The Big Picture	**Moderator: Dr. Lethia S. Jackson**, Bowie State University **AJ Gemer**, Lunar Outpost **Dr. Stephen Hart,** TRAClab **Dr. Hazel Edwards**, Howard University
2:10	Breakout Scenarios and Guidance	
2:20	*Break – transition to breakout sessions*	
2:30	Breakout Session 1: Establishing Infrastructure on the Lunar Surface	
3:25	*Break*	
3:35	Breakout Session 2: Operating Infrastructure on the Lunar Surface	
4:30	*Break*	
4:40	Breakout Session 3: Maintaining Infrastructure on the Lunar Surface	
5:35	*Break – transition back to plenary*	
5:45	Wrap up, final thoughts, path forward	
6:00	*Adjourn Meeting*	

Speakers

Dr. Angel Abbud-Madrid

Director, Center for Space Resources
at the Colorado School of Mines

Dr. Angel Abbud-Madrid is the Director of the Center for Space Resources at the Colorado School of Mines, where he leads a research program focused on the human and robotic exploration of space and the utilization of its resources. He is also the Director of the Space Resources Graduate Program, aimed at educating scientists, engineers, economists, entrepreneurs, and policy makers in the field of extraterrestrial resources. He has more than 30 years of experience in space projects on NASA's drop towers, microgravity aircraft, the Space Shuttle, and the International Space Station and received the NASA Astronauts' Personal Achievement Award for his contributions to human spaceflight. He is currently the President of the Space Resources Roundtable international organization and member of the Committee on Planetary Protection of The National Academies of Sciences, Engineering, and Medicine.

Dr. Danette Allen

Senior Technologist (ST) for Intelligent Flight Systems,
Deputy Lead of Systems Capability Leadership Team (SCLT)
for Autonomous Systems (AS-SCLT), NASA

Dr. Danette Allen is NASA's Senior Technologist (ST) for Intelligent Flight Systems and Deputy Lead of the Agency's Systems Capability Leadership Team (SCLT) for Autonomous Systems (AS-SCLT). She created and led the Autonomy Incubator at NASA Langley Research Center (LaRC) and, following that, served as co-PI of the ATTRACTOR (Autonomy Teaming & TRAjectories for Complex Trusted Operational Reliability) project, focused on trust and trustworthiness of autonomous systems. Dr. Allen earned her B.S. degrees in Electrical Engineering and Computer Engineering from North Carolina State University, MBA from Manchester University (UK), M.E. in Computer Engineering from Old Dominion University, and M.S. and Ph.D. in Computer Science from UNC Chapel Hill. Dr. Allen is the recipient of multiple NASA awards including the astronauts' "Silver Snoopy" award for achievements related to human flight safety and mission success, the "Systems Engineering Excellence Award" medal, and the "Outstanding Leadership" medal. She is an ACM Member, an AIAA Associate Fellow and a member of the AIAA Intelligent Systems and the Human Machine Teaming Technical Committees.

Speakers

The Honorable Angela D. Alsobrooks

Executive, Prince George's County, MD

In November 2018, Angela, a proud, lifelong Prince Georgian, was elected as the 8th County Executive for Prince George's County and the first woman to hold the position. Her administration is committed to providing a world-class education system, safe communities and a robust economy that creates jobs and opportunities for all and increases the commercial tax base to ensure residents are provided with the services they deserve.

In 2010, Angela was elected to serve as the county's State's Attorney, becoming the youngest and first woman to be elected to the office in Prince George's County. As the county's top law enforcement official, Angela played a key role in public safety and strived to carry out her responsibilities in a firm, fair and consistent manner. She fought for additional resources to ensure the office could appropriately support the needs of the community.

Angela received her B.A. in Public Policy from Duke University and her J.D. from the University of Maryland School of Law. She is a member of the First Baptist Church of Glenarden and Delta Sigma Theta Sorority, Inc.

Daniel Andrews

VIPER Project Manager, NASA

Daniel Andrews is the Director of Engineering at NASA's Ames Research Center, detailed to lead the VIPER rover mission to the moon. Dan has been working closely with NASA-Headquarters in Washington DC to develop the first US robotic rover mission to the moon, VIPER. This mission follows on the heels of the ground-truthing LCROSS mission, which he also led, confirming the presence of billions of gallons of water-ice on the South Pole of the Moon.

Dan is known in NASA for leading capabilities-driven, cost-effective missions. Dan received his Bachelor's degree in Electrical Engineering from San Jose State University and his Master's degree in Mechanical Engineering from Stanford University. He started his career at NASA's Ames Research Center as an automation and controls engineer working on many diverse robotic technology demonstration projects, including development of a 3-axis Exobiology Robotic Table, a Serpentine Robot, an Autonomous Rotorcraft, and the Personal Satellite Assistant (PSA) Project - a free-flying robot astronaut assistant, garnering the attention of Newsweek, Popular Science, and Air & Space Magazine, and was named one of the "50 Best Robots Ever" in Wired Magazine.

Dan has received numerous NASA awards including the Outstanding Leadership Medal and the Exceptional Achievement Medal, as well as several Group Achievement awards. His teams have received a number of industry awards such as Popular Mechanics' Breakthrough Award, the Space Foundation's "John L. 'Jack' Swigert Jr. Award for Space Exploration", and the National Space Society's Space Pioneer Award.

Speakers

Matt Atwell

Project Manager, Intuitive Machines

Matt Atwell is an engineer and project manager at Intuitive Machines, where he works on their Lunar Payloads and Data Services program. He is currently serving as the Project Manager for the NASA STMD-funded Tipping Point Micro-Nova Hopper, and is responsible for leading the development, testing, integration, and execution of this spacecraft's first demonstration mission on the lunar surface. Matt is also the responsible engineer for numerous propulsion system elements on the Nova-C lunar lander, including the main engine igniter, pressurization system, and thermodynamic vent system. Before working at Intuitive Machines, Matt spent eight years at NASA, where he worked on spacecraft propulsion system design, development, testing, and operations. In his time there he supported Project Morpheus, Seeker, the Orion Crew and Service Modules, and various cryogenic propulsion system technology development projects.

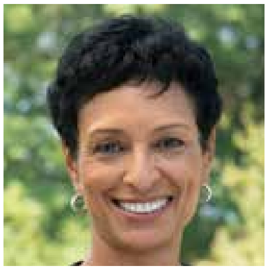
Dr. Anika A. Bissahoyo

Assistant Vice President for Research at Bowie State University

Dr. Anika Alfred Bissahoyo is the Assistant Vice President for Research at Bowie State University (BSU). She earned her bachelor's degree in Molecular Biology and Biochemistry from the University of Maryland Baltimore County and her doctorate in Toxicology from the University of North Carolina at Chapel Hill. Dr. Bissahoyo has previously served as Director of Development and Proposal Writer at Claflin University in Orangeburg, SC, Director of Sponsored Programs at Bradley University and as a Data Analyst for the Leadership Alliance Program at Brown University.

At Bowie State University, Dr. Bissahoyo manages the University's portfolio of extramural grants and has supported the campus in achieving a 99% increase in external funding over the past 4 years. She also supports the University seeking strategic partnerships and resources for education and research innovation. Dr. Bissahoyo also oversees the Office of Undergraduate Research and co-administers the Summer Undergraduate Research Institute at the University that has provided approximately 200 undergraduate students with faculty-mentored research experiences over the past 5 years at BSU. She is also a PI on a National Institutes of Health (NIH) award from the National Institute of General Medical Sciences to bolster the University's capacity in the areas of biomedical, behavioral and social science research and in pursuing NIH funding.

Speakers



Dr. Aminta H. Breaux

President, Bowie State University

Dr. Aminta H. Breaux has served as the 10th president of Bowie State University since July 2017, bringing more than 30 years of diverse higher education leadership experience to the position. She is dedicated to building on the legacy and rich history of Maryland's oldest historically black university with a strategic focus on ensuring the long-term viability of the institution. She has been tapped to serve in multiple leadership roles, including the President's Board of Advisors on Historically Black Colleges and Universities and the Governor's P-20 Leadership Council of Maryland. She also sits on the board of directors of the Greater Prince George's Business Roundtable, the Prince George's County Chamber of Commerce and the University of Maryland Capital Region Health. She also serves as vice chair of Board of Directors for the Central Intercollegiate Athletic Association, and is also a member of the Board of Trustees of the Strada Education Network.

Previously, Dr. Breaux served as vice president for advancement for Millersville University, and as vice president for student affairs at Millersville. She also held administrative positions at University of the Sciences in Philadelphia and Drexel University after beginning in higher education at the University of Pennsylvania. She earned a doctorate in counseling psychology from Temple University, a master's degree in psychological services in education from the University of Pennsylvania and a bachelor's degree in psychology from Temple University. She is also a graduate of the Harvard Institute for Executive Management and the American Association for State Colleges and Universities Millennium Leadership Institute.

Dr. Josh Cahill

Deputy Director, LSIC

Senior Staff Scientist, JHU Applied Physics Laboratory

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

Speakers

AJ Coleman

Program Lead Deputy, Joint Polar Satellite Systems (JPSS) program

AJ Coleman is the Program Lead Deputy for the Joint Polar Satellite Systems (JPSS) program for SAIC on NASA's Omnibus Multidiscipline Engineering Support (OMES) II contract at the Goddard Space Flight Center in Greenbelt, MD. Mr. Coleman has worked in the aerospace industry for over 15 years and has a background in systems engineering, and satellite and flight operations. During his extensive career, Mr. Coleman held several engineering leadership positions with HTSI, KBRwyle, and now SAIC. Mr. Coleman is a graduate of Morgan State University with a Bachelor's of Science in Physics, and resides in Maryland with his wife and daughter.

Dr. Hazel Edwards

Professor and Chair of the Department of Architecture, Howard University

Dr. Edwards' career combines place-based research with planning and urban design practice and teaching. Her research interests in livability are framed within urban contexts while focused primarily on historic campus environments. This orientation has enabled a particular interdisciplinary approach to architecture, sustainable design, and city planning. She has been a member of several American Institute of Architects and American Planning Association volunteer teams focused on developing alternatives to complex urban design (UDAT), planning (PAT), community planning (CPAT), and sustainable design assessment (SDAT) challenges.

Dr. Edwards graduated from Howard University (Bachelor of Architecture). She went on to earn degrees from Harvard University (Master of Architecture in Urban Design) and the University of Illinois—Urbana-Champaign (Ph.D. in regional planning). She taught in the graduate planning program in the Institute of Architecture and Planning at Morgan State University (1999-2007) before joining the faculty at the School of Architecture and Planning at The Catholic University of America in 2007. In July 2016, she joined the College of Engineering and Architecture at Howard University as Professor and Chair of the Department of Architecture.

At Howard, she is one of the Principal Investigators of a seven-institution research team funded by NASA. The Habitats Optimized for Missions of Exploration (HOME) Space Technology Research Institute for Deep Space Habitat Design, is one of two space technology research institutes selected by NASA in 2019. Howard architecture faculty and students are investigating earth-bound settings for adaptive architecture with potential applications to zero-/partial- gravity space habitats.

Speakers

Dr. Terry Fong

Senior Scientist for Autonomous Systems, NASA

Dr. Terry Fong is NASA's Senior Scientist for Autonomous Systems and the deputy rover lead for NASA's 2023 VIPER lunar rover mission. He is also Chief Roboticist and former Director of the Intelligent Robotics Group (IRG) at the NASA Ames Research Center. Dr. Fong previously served as project manager for the NASA "Human Exploration Telerobotics" project, which developed and tested advanced telerobotic systems (Astrobee, Robonaut 2, Smart SPHERES, and Surface Telerobotics) on the International Space Station. From 2002-2004, Dr. Fong was the deputy leader of the Virtual Reality and Active Interfaces Group at the Swiss Federal Institute of Technology (EPFL). From 1997-2000, he was Vice President of Development for Fourth Planet, Inc., a developer of real-time visualization software. Dr. Fong has published more than 150 technical papers in space and field robotics, human-robot interaction, virtual reality user interfaces, and planetary mapping. Dr. Fong received his B.S. and M.S. in Aeronautics and Astronautics from the Massachusetts Institute of Technology and his Ph.D. in Robotics from Carnegie Mellon University.

Mark J. Fuerst

Program Manager Director for SAIC

Mark Fuerst is the Program Manager Director for SAIC on NASA's Omnibus Multidiscipline Engineering Support (OMES) II contract at the Goddard Space Flight Center in Greenbelt, MD. He has worked in the aerospace industry for 45 years with nearly 20 of those years supporting NASA and NOAA at GSFC. During his career, he has held leadership positions with Raytheon, Honeywell, Columbus Technologies, SGT, and now SAIC. He is a graduate of the University of Maryland University College with a Bachelor's of Science in Business Management, attended George Washington University, and is a certified Project Management Professional (PMP). He has served on the Board of Directors for his church, the Goddard Contractor Association, the Goddard Advocacy Partnership, and The Samaritan Women (a group focused on fighting human trafficking and ministering to the needs of its victims). He is a past President with the Rotary Club of Greenbelt and a Rotarian for over ten years. He has travelled to Lusaka, Zambia nine times since 2011 working with orphan and vulnerable children with the Family Legacy Ministries. Mark and his wife of 47 years live in nearby Berwyn Heights, MD and have been a resident of Prince George's County Maryland nearly their entire lives. They have three children and three grandchildren.

Speakers

AJ Gemer

Chief Technology Officer, Lunar Outpost Inc.

Andrew Josef (AJ) Gemer is the CTO of Lunar Outpost, where he directs the technology roadmaps and infusion plans for new, enabling technologies aboard LO's line of Mobile Autonomous Prospecting Platform lunar rovers, in parallel with the development of Earth-analog extreme environment robotic platforms for development and maturation of future customer payloads. AJ, as a PI on a NASA contract, led the design of a thermal management system for MAPP to allow for robotic systems lunar night survival and permanently shadowed region exploration. Prior to co-founding Lunar Outpost, he worked at the Laboratory for Atmospheric and Space Physics on a number of spaceflight scientific instruments including the Colorado Student Space Weather Experiment (CSS-WE), the Nano-Dust Analyzer (NDA), the Surface Dust Analyzer (SUDA), and the Hyperdust dust trajectory sensor and impact mass spectrometer. He holds M.S. degrees in both Mechanical and Aerospace engineering from the University of Colorado at Boulder, where his research included in-situ mass spectroscopy of interstellar and interplanetary cosmic dust, effects of hypervelocity impacts on spaceflight instruments and glasses, and topology optimization of spaceflight structures and composites. Recent publications include "Advanced In-Situ Detection and Chemical Analysis of Interstellar Dust Particles" and "The Effect of High-Velocity Dust Particle Impacts on Microchannel Plate (MCP) Detectors."

Dr. Stephen Hart

Senior Scientist, TRACLabs, Inc.

Dr. Hart is a Senior Scientist with the Robotics group at TRACLabs, Inc., a small business located in Webster, Texas, near NASA Johnson Space Center. Dr. Hart's research focuses on developing software that make programming complex, sensor-driven robots easier, without sacrificing their flexibility and capabilities in real-world contexts. He has previously worked at the Italian Institute of Technology, General Motors R&D, and onsite at NASA, where he was the "Behavior & Applications Lead" for both the Robonaut 2 and Valkyrie humanoid systems. At TRACLabs, Dr. Hart has led and participated in a number of projects and has integrated his software within NASA and in commercial contexts. As software lead for the TRACLabs DARPA Robotics Challenge team, he led the team of six programmers and researchers to a 9th place finish (out of 23 competing teams) at the 2015 DRC finals. Software development activities for NASA and TRACLabs have included the development of the ROS-based CRAFTSMAN robot application tool suite, the Affordance Template Task Description Language, and Robot Task Commander. Research projects have included enabling robot applications through human-readable checklist procedures, the investigation of closed-loop control techniques for high-level behavioral programs, bridging ROS with the NASA Core Flight System, and symbolically grounding ontological knowledge representations in the run-time performance of dynamical systems.

Speakers

Dan Hendrickson

Vice President of Business Development, Astrobotic Technology

Dan Hendrickson leads Astrobotic Technology's business development efforts and growth, which include two lunar lander missions, and more than 15 Lunar payload customers to date. Prior to Astrobotic, Hendrickson served as the Director of Civil and Commercial Space Systems at the Aerospace Industries Association (AIA). During his time at AIA, Mr. Hendrickson was a consensus builder among a council of 50 U.S. space companies to provide the U.S. Government guidance on key space industry interests. Before transitioning to AIA, Mr. Hendrickson served as a civilian mission assurance engineer at Cape Canaveral Air Force Station on five successful Atlas V launch campaigns.

Dr. Lethia S. Jackson

Professor and Chair, Department of Technology and Security, Bowie State University

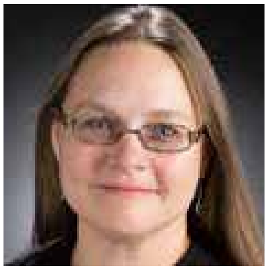
Dr. Lethia Jackson, a full professor and founding chair of the Department of Technology & Security. Dr. Jackson holds a terminal degree in Computer Science from The George Washington University, a Master's degree in Computer Science from North Carolina State University and a Bachelor's of Science degree in Computer Science from North Carolina Agricultural and Technical University Later, she completed a Post-Doctoral Certificate in Academic Leadership from The Chicago School of Psychology in Washington, DC. In 2012 – 2013, she was a member of Preparing Critical Faculty for the Future, Next Generation STEM Learning: Investigate, Innovate, Inspire, funded by National Science Foundation.

Listed as one of 1000 Inspiring Black Scientist in America posted by The Community of Scholars, Jackson has acquired over twenty (20) industry and government partners who have provided internships, equipment donations, membership on the external advisory board, academic training modules, industry-level certifications, articulation agreements, and service-learning projects to the department. Additionally, she structured a collaboration with four in-state and out-of-state entities including universities, businesses, public school districts, and community colleges utilizing a $25 Million dollar grant opportunity.

Jackson has secured and administered more than $2.5 million in proposals, grants and contracts from the federal government and private sector companies, including the Department of Energy, Northrop Grumman, Honeywell, IBM, and Stinger-Ghaffarian Technology. She has written and spoken on cybersecurity, as well as the infusion of technology in the local public school systems to include Prince George's, Howard and Baltimore City Counties.

Jackson is married and has five children, four females and one male. The oldest three of the five children are young hard working adults who are graduates of Bowie State University majoring in Computer Technology with emphasis in Cybersecurity and Programming.

Speakers

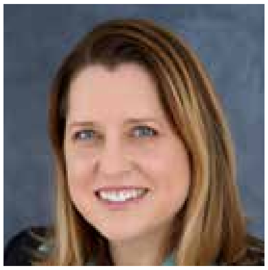


Dr. Rachel Klima

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.



Dr. Cara E. LaPointe

Co-Director, Institute for Assured Autonomy,
JHU Applied Physics Laboratory

A futurist who focuses on the intersection of technology, policy, ethics, and leadership, Dr. Cara LaPointe is the co-director of the Johns Hopkins Institute for Assured Autonomy, which works to ensure that autonomous systems are safe, secure, and trustworthy as they are increasingly integrated into every aspect of our lives.

During more than two decades in the United States Navy, LaPointe held numerous roles in areas including autonomous systems, acquisitions, ship design, naval force architecture, and unmanned vehicle technology integration. At Woods Hole Oceanographic Institution's Deep Submergence Lab, she conducted research in underwater robotics, developing sensor fusion algorithms for deep-ocean autonomous underwater vehicle navigation.

LaPointe was previously a senior fellow at Georgetown University's Beeck Center for Social Impact + Innovation, where she created the "Blockchain Ethical Design Framework" as a tool to drive social impact and ethics into blockchain technology. She has served as an advisor to numerous global emerging technology initiatives, including at the United Nations and the Organization for Economic Co-operation and Development. LaPointe is a patented engineer, a White House Fellow, and a French American Foundation Young Leader. She served under two administrations as the interim director of the President's Commission on White House Fellowships.

LaPointe holds a Doctor of Philosophy, awarded jointly by the Massachusetts Institute of Technology (MIT) and WHOI, a Master of Science and a Naval Engineer degree from MIT, a Master of Philosophy from the University of Oxford, and a Bachelor of Science from the United States Naval Academy.

Speakers

Brett Lindenfeld

Vice President of Programs, Motiv Space Systems, Inc.

Mr. Brett Lindenfeld has over 28 years of experience in various engineering, management, and leadership roles at the Jet Propulsion Laboratory (JPL), MDA US Systems (Formally ASI) and now as a co-founder of Motiv Space Systems, Inc. Starting with roles in mechanical systems engineering, Mr. Lindenfeld later held positions of Director of Engineering, VP of Operations and VP of Programs, ultimately being responsible for every project undertaken in nearly 18 years of his tenure. Prior to MDA, Mr. Lindenfeld was a Member of the Technical Staff at JPL for 5 years. Brett's career includes managing the design, execution and delivery of several robotic manipulator activities including: the MER IDD for Spirit and Opportunity, the Mars Phoenix Lander Robotic Arm, the DARPA FREND Robotic Arm for satellite servicing, the MSL Curiosity Rover Robotic Arm, the Mars Insight Robotic Arm, the control system for the Restore-L servicing arm at NASA GSFC, the Mars 2020 Perseverance Robotic Arm, and now NASA's COLDArm for future lunar missions demonstrating extreme environment operations. Brett continues to enable NASA and commercial partners through robotic product developments as well as guide the evolution of new technologies to challenge the state of the art in robotic capabilities as well as motion control applications in extreme environments. Mr. Lindenfeld carries a BS in Aerospace Engineering from the University of California, Los Angeles.

Candice Matthews Brackeen

General Partner, Lightship Capital

Candice Matthews Brackeen is a General Partner at Lightship Capital, the Cincinnati-based firm investing in the most remarkable innovators and ecosystems across the nation with a focus on CPG, E-Commerce, Sustainability, Artificial Intelligence, and Healthtech.

Candice also serves as Executive Director and Founder of Lightship Foundation, an impact-driven organization enabling growth within the minority innovation economy. Her dedication to moving inclusion in innovation forward is also reflected in her advisory roles across numerous organizations including the Lunar Surface Innovation Consortium for NASA, where she leads diversity of thought as the United States of America harnesses and accelerates technology toward a sustainable return of humans to the Moon's surface.

Candice also serves on the Cincinnati Innovation District Advisory Council, the Endeavor Northwest Arkansas Board of Directors, and is a University of Cincinnati Kautz Uible Fellow.

Speakers

Lt Col Rock McMillan

Director, SpaceWERX

Lt Col Walter "Rock" McMillan is the Director of SpaceWERX. Lt Col McMillan entered the Air Force in 2003 through the University of Southern California ROTC program. He has served in a variety of program management and staff positions within Air Force Materiel Command, Pacific Air Forces, Air Force Space Command, and Office of the Assistant Secretary of the Air Force for Acquisition. He served as a Program Element Monitor for Military Satellite Communications programs and as Congressional Liaison Officer, House Division, Office of Legislative Liaison.

Prior to returning to Los Angeles AFB, Lt Col McMillan attended the Air Officer Commanding Master's Program in Colorado Springs, Colorado. He then became the Air Officer Commanding for Cadet Squadron 22 at the United States Air Force Academy in Colorado Springs, Colorado.

Michael Mealling

General Partner, Starbridge Venture Capital

Michael has been fighting ' chicken and egg' problems since 1990. Whether it's building information systems into the core of the internet in 1995, or working to kickstart a cislunar economy in 2020, he is constantly drawn to complex, multi-stakeholder efforts where the end state can be determined, but the start is unknown.

Circa 2002, Michael noticed that, while there were signs that a purely commercial space industry could exist, a majority of the nascent players were far too focused on the technology rather than building sustainable businesses especially in light of what the internet sector had done during the previous decade. In 2004, he joined Dave Masten and a few others to build Masten Space Systems as the team's VP of Business Development and CFO. For the following six years, the team struggled to raise money and test VTVL rockets. Eventually, the company hit significant milestones and won $1.1M in prize money from NASA.

During this time, he became a leader within the Space Frontier Foundation and the Moon Society where he has been President since 2017. The Moon Society is a citizen advocacy group focused on human Lunar development. Michael represents the Society as a board member with the Alliance for Space Development, a group of citizen-led space advocacy organizations working to inform policymakers of our joint views on space development and settlement.

In 2011, Michael received an MBA from Georgia Tech and began working with others building a satellite ground station network which was eventually folded into RBC Signals. Following this, he joined Seraph Group, an early stage, general technology venture capital fund in Atlanta, GA, and led due diligence efforts with several aerospace-related deals; namely Planetary Resources and Boom Aerospace. Back then, few venture capital investors knew how to evaluate emerging space companies. Today, Michael is a General Partner at Starbridge Venture Capital, an early-stage, space technology venture fund that is focused on financial returns for its investors. That focus requires the Starbridge team to be relentless about which businesses are real, which ones are merely speculative, and generally where the industry is going over the next twenty-five years. Starbridge is known for what it doesn't invest in rather than what it does.

Speakers

Josephine Millward

Strategic Advisor, Seraphim Capital

Josephine brings more than a decade of experience in investment/equity research following the aerospace industry. Her research coverage has included a wide range of small-to-mid cap Defence and Security Technology companies, such as space (DigitalGlobe and GeoEye), drones (AeroVironment) robots (iRobot), and threat detection. She worked most recently at the Benchmark Company, where she established a Washington D.C. office prior to relocating to Paris, France. She began her equity research career covering Global Communications at JP Morgan. Josephine received her MBA from Georgetown University and bachelor's degree from the University of California, Riverside.

Dr. Jamie Porter

Extreme Environments Focus Area Lead, LSIC

Raditation Effects Engineer, JHU Applied Physics Laboratory

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

Speakers

James Reuter

Associate Administrator for Space Technology, NASA

James L. Reuter was named NASA's associate administrator for the Space Technology Mission Directorate (STMD) at NASA Headquarters in June 2019, a position in which he served in an acting capacity since February 2017. In this role, he provides executive leadership and management of the technology programs within STMD, with an annual investment value of $1.1 billion.

Reuter was the deputy associate administrator of STMD from February 2017-February 2018. Prior to this role, Reuter served as the senior executive for technical integration in the Center Director's Office at NASA's Marshall Space Flight Center from 2009-2015, providing strategic leadership on critical technology and integration activities. Additionally, Reuter served as the Exploration Systems Division (ESD) Standing Review Board chair, responsible for overseeing development activities of the Space Launch System, Orion Multi-Purpose Crew Vehicle, Ground Systems Development and Operations Programs, and the ESD integration activities.

Previously, Reuter served in many managerial roles at Marshall including Ares vehicle integration manager in the Constellation program, the deputy manager of Space Shuttle Propulsion Office, and the deputy manager of Space Shuttle External Tank Project Office during the shuttle return-to-flight activities. In 2002, he was assigned to a detail at NASA Headquarters as the deputy associate director in the Space Transportation Technology Division in the Office of Aerospace Technology. From 1994 to 2001, he was the Environmental Control and Life Support System manager for the International Space Station at NASA's Johnson Space Center. Reuter began his NASA career in 1983 as an aerospace engineer in the Structures and Propulsion Laboratory in Marshall's Science and Engineering Directorate.

Reuter has a bachelor's degree in mechanical engineering from the University of Minnesota in Minneapolis. He has received numerous NASA awards and honors, including a 2019 Distinguished Service Medal, 2016 Outstanding Leadership Medal, 2013 NASA Exceptional Achievement Medal, a 2008 NASA Outstanding Leadership Medal, a 2002 NASA Exceptional Service Medal, a 1998 Silver Snoopy Award and a 1993 Space Station Award of Merit.

Curtis Rodgers

Industrial Technologist and Investor, Brick & Mortar Ventures

Curtis Rodgers is an industrial technologist and investor at Brick & Mortar Ventures, with six years of construction process improvement experience at both Kiewit and McCarthy Construction — across federal, industrial, infrastructure, and commercial markets. Curtis founded The Society for Construction Solutions (SCS) in 2014, contributed to the NASA Centennial 3D Printed Habitat Challenge, and participated as a lecturer for the US Dept. of Energy's Project Leadership Institute. Curtis holds a B.B.A. in Management and an M.S. in Technology from Texas State University-San Marcos.

Speakers

Jason Schuler

Principal Investigator, ISRU Pilot Excavator, NASA

Jason is a mechanical engineer and founding member of Swamp Works – a team at Kennedy Space Center devoted to developing robotic technologies to use space resources. He is a co-inventor of RASSOR - aka Regolith Advanced Surface Systems Operation Robot and has spent the last 14 years developing technologies that will interact with extra-terrestrial regolith. Jason is currently the Principal Investigator for the ISRU Pilot Excavator project to develop a robotic system to demonstrate large scale lunar regolith excavation on a future CLPS mission.

Kevin Somervill

Technical Integration Manager for Extreme Environments, NASA

Kevin Somervill is NASA STMD Technical Integration Manager for Extreme Environments. He has over fifteen years of development experience at Langley Research Center, with the last ten years leading multi-center, multi-disciplinary teams. His expertise is in data systems development and worked on projects including from Earth Observing science instruments, reconfigurable computing, and instrumentation for materials and cryogenic applications. In his current role, Mr. Somervill supports STMD fostering technology development to enable sustained lunar surface operations in support of NASA mission objectives.

Amanda Stadermann

Senior PhD Candidate, Lunar and Planetary Laboratory, University of Arizona

Amanda Stadermann (she/her) is a senior PhD candidate at the Lunar and Planetary Laboratory at the University of Arizona, where she studies the geochemistry and petrology of lunar rocks using primarily electron microscopy. As the Communications Lead on the Organizing Committee for the Next Generation Lunar Scientists and Engineers (NGLSE, NextGen) group, Amanda serves NGLSE and the broader lunar community by advocating for and supporting early career professionals who are to become the future lunar workforce.

Speakers

Niki Werkheiser

Director for Technology Maturation, Space Technology Mission Directorate (STMD), NASA

Niki Werkheiser serves as the Director for Technology Maturation in the Space Technology Mission Directorate (STMD) at NASA Headquarters, where she leads the advancement of mid-TRL technologies for future space missions. The Technology Maturation portfolio includes more than 120 projects within the Game Changing Development (GCD) Program and the Lunar Surface Innovation Initiative (LSII). These ambitious projects are executed across eight NASA Centers and with dozens of industry and academic partners.

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

Ms. Werkheiser holds a Master of Science Degree from the University of Alabama at Huntsville with an emphasis in Gravitational and Space Biology, as well as a Bachelor of Science in Biology and a Bachelor of Arts in Russian Language and Studies.

Table of Contents for Abstracts

Recap of the Inaugural Semester of *Operating in the Lunar Environment*.

A. C. Ekblaw[1] and S. P. Auffinger[2], [1]Director, MIT Space Exploration Initiative, 77 Mass. Ave., E14-574A, Cambridge, MA 02139-4307 USA. [2]Mission Integrator, MIT Space Exploration Initiative, 77 Mass. Ave., E14-574A, Cambridge, MA 02139-4307 USA. (Contact: aekblaw@mit.edu, seanauff@mit.edu)

Introduction: In Spring 2021, the MIT Space Exploration Initiative and MIT AeroAstro hosted the first edition of the course: *Operating in the Lunar Environment*, bolstered by NASA's announcement of the Artemis program to return to the Moon with the first Man and next Woman, leading to a renewed focus across the space industry on lunar exploration. Over the next decade, NASA will be pursuing partnerships across industry and academia to plan a series of precursor robotic missions, hoping to uncover new insights into the challenges and opportunities associated with operating on the lunar surface. Eventually, the goal is to establish a continued and sustainable human presence, making use of local resources such as lunar volatiles and reserves of water-ice discovered in the lunar polar regions.

Pedagogical Approach: The course aimed to expose students to the technological, scientific, political, and economic challenges associated with lunar exploration, while offering opportunities to gain direct, hands-on experience with developing lunar hardware. Instructors Professor Jeffrey Hoffman from MIT AeroAstro, and MIT Space Exploration Initiative Founder and Director Ariel Ekblaw, drew on their own experiences developing hardware for the harsh space environment. Students were also able to interact with and learn from a series of guest speakers with direct experience developing hardware for the lunar environment, including industry representatives from organizations such as the Jet Propulsion Laboratory, Draper Laboratory, Lockheed Martin, and even former retired Apollo Engineers.

Throughout the semester, students worked on two distinct projects: an individual "Mission Concept" plan for an innovative near-future mission to the moon, and a team "Payload Project", developing actual hardware for existing MIT Lunar missions. Each project was refined with special "office hours" sessions and subjected to a rigorous set of design reviews with feedback from the industry guests.

Democratizing Access: This course offering falls under the ethos of the MIT Space Exploration Initiative of democratizing access to space. While there were many students from the AeroAstro department at MIT, students from other departments and schools were encouraged to join. Additionally, as much course content as possible, including the syllabus, lecture recordings, and slides, was made open-access and is available on the course website [1].

Outcomes: Four payload projects were developed as part of the course, with additional development on each currently ongoing. Course funding was used to create professional rendering of each for use in future publicity and grant opportunities. Additionally, the MIT Space Exploration Initiative is moving towards securing a near-term launch opportunity to the moon, with the goal to include several payloads that participated in the course.

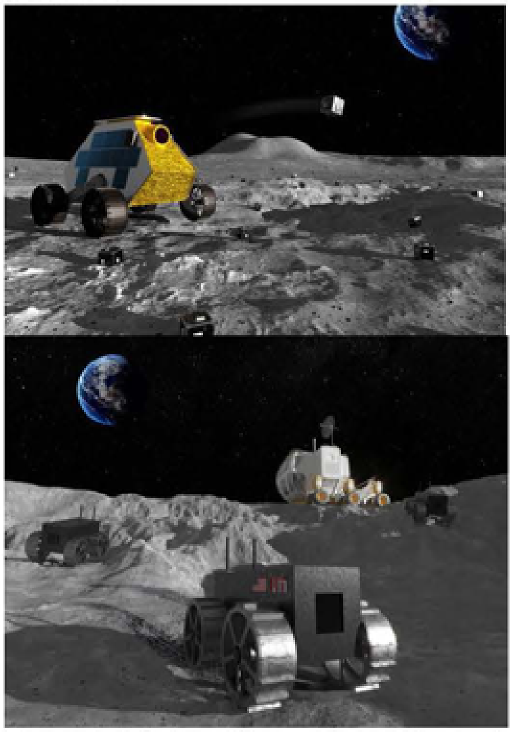


Figure 1. Artist renditions of two of the payloads developed during the course.

References:

[1] https://tothemoon.pubpub.org/

Orchestrating Symbiosis: Foundational technologies for Human, Robotic, and Autonoma Shared Control – Exploring the Framework.

Gary P. Barnhard[1]

Introduction:

All those involved in understanding, architecting, and implementing shared control relationships between humans, robotics, and autonoma need a framework that encompasses both the problem space and provides for articulating non-null solution spaces which are both satisfactory and sufficient. Motivating and embracing worldviews that allow for the same will challenge our expectations in no uncertain terms.

In the most general sense, the Problem Space is that of N-Dimensional interaction problems (i.e., an arbitrary number of objects interacting in an arbitrary number of ways). These are a class of problems for which the generalized solution space is typically computationally intractable in any time frame. Space autonoma and robotics present a subset of these problems that exacerbates the situation by requiring near real-time solutions in many instances. Alas, "reality" is not a convenient problem or solution space.

Accordingly, this leaves us in a quest to find nexus: in this case, the intersection between theoretical constructs of knowledge-based systems and space systems engineering reduced to practice. The mission development efforts presented can be viewed as a set of conceptual threads intended to draw out the confluence of interests needed to bias work towards better "outcomes" for Cislunar and beyond space missions.

Creating a framework and foundation for a mutable locus of shared control is an investment in a positive future, not a dystopian one. How we come to own our own choices, take responsibility for our own actions, and be stewards for life as we come to understand it will define our species.

In the near term, our success in building a symbiotic relationship between humans, robots, and autonoma will be a crucial driver in developing Cislunar space. In the long term, our success in the same could prove to be a determining factor in the fate of our species.

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Investigating the Effects of Product, Market, and Transportation Propellant on the Efficiency/Economics of Lunar Water Derived Propellant.

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

Introduction: We hope lunar derived propellants will play a role both in a continuing human presence on the Moon and in facilitating cislunar activity of all kinds. Both water and regolith oxygen could play a roll, but to avoid a treatment for relative costs we restrict this analysis to water products. We perform the analysis and present the results in economic terms, taking the role of a commercial lunar propellant enterprise. However, this approach is dual to an efficiency analysis, which we believe would reach the same conclusions.

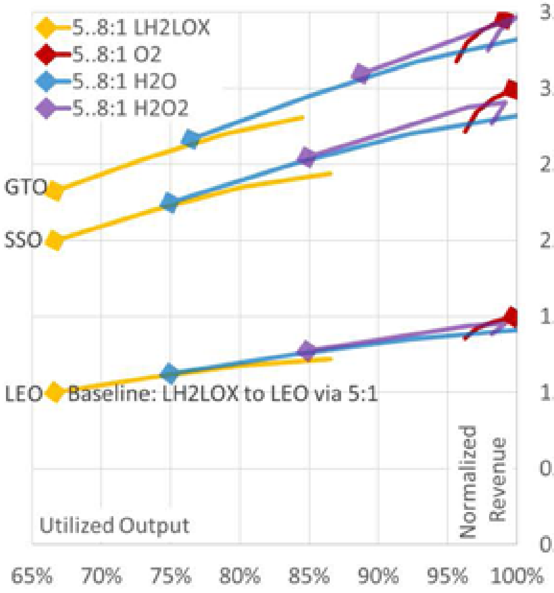

Figure 1: Utilized Output x Normalized Revenue/Utility of Products, Markets, and O:F ratios

Products: Once obtained on the lunar surface water can be used to produce several propellant products, most commonly hydrolox. Choosing regular (5.6:1 oxidizer to fuel) hydrolox as a product ensures a significant opportunity loss; 27% of the mass of procured water is excess oxygen, if this is discarded it represents significant implicit underutilization of infrastructure investment. The excess oxygen is orders of magnitude greater than any reasonably conceivable life support demand; this observation motivates investigating what happens if the propellant product is oxygen, or other high oxygen propellants one can produce from water. Hydrogen peroxide is a useful green station keeping propellant, and there is the prospect of solar and electric water engines.

Markets: LEO is a commonly analyzed market for lunar propellant, but GTOs and SSOs are also likely. Many satellites are in very similar orbits in SSOs, and so there is potential for aggregated demand. About 20 GTO orbit ratings occur annually, and we can generalize to HEEOs, like LDHEOs, as interplanetary staging orbits. One must burn propellant to deliver propellant, so each market has different transportation costs from the Earth or the lunar surface. Transportation propellant requirements allow us to derive delivered mass fraction of lunar production and the utility of delivered product.

Transportation Propellant: Apollo's J2 engine varied its O:F ratio between 5.5:1 and 4.5:1 to tune thrust and propellant burn up. We analyze the effect, but not the practicality of higher O:F ratios (up to water stoichiometric). One potential stumbling block that has been called out is higher combustion temperatures. However, for an expander cycle engine like the RL-10 one of the factors that limits size is that the heat exchange area available to power the pumps scales more slowly than the combustion chamber volume and mass flow, hotter combustion might allow larger engines.

Conclusions: Our conclusions can be read off Figure 1. Unsurprisingly it pays to sell in high energy orbits, but, an appropriate choice of product and transportation O:F ratio can boost revenue/utility by 50% over the baseline "sell hydrolox". Oxygen in HEEOs seems the most compelling product given current hydrolox engines. Oxygen could contribute to any transportation use-case in cislunar space, including interplanetary injections. Adding high O:F ratio engines to the lunar tankers allows close to maximum revenue/utility to be extracted when supplying H2O and H2O2. Only when hydrolox customers also use high O:F ratio engines is it desirable to supply hydrolox. Finally, if a lunar enterprise can compete against Earth hydrolox then it has a significant incentive to develop high O:F engines, it then has the capability to expand into providing both transportation services that use lunar surface water more efficiently and the engine technology itself.

An Introduction to the Space Robot Operating System. S. Will Chambers, Blue Origin Advanced Development Programs, 20819 72nd Ave S.Kent, WA 98032, (Contact: schambers@blueorigin.com)

Introduction: A sustainable lunar presence requires robotic and autonomous space systems to perform tasks ranging from in-situ resource utilization, excavation and construction, inspection and repair, and power generation and distribution. Common to these systems is the need for a robust flight-quality software that is certifiable to mission and safety assurance standards. Although such software frameworks like Core Flight System [1] exist for spacecraft, there currently does not exist a comparable space-quality software framework designed for robotic and autonomous space system.

Space Robot Operating System. Blue Origin, in collaboration with NASA, is leading the technical maturation of Space Robot Operating System (Space ROS), a space-quality software framework designed specifically for autonomous and robotic space systems and missions. Space ROS software includes communication middleware, core software packages and application software packages that enable autonomous and robotic lunar systems to reliably execute their tasks. Application packages provide the operational functionality critical to lunar operations, and include robotic manipulation, mobility, autonomy and collaboration software kits. Space ROS will also define an agent communication language and space ontology that allows robotic space systems share information, allocate task, and form coalitions.

Space ROS is predicated on open-source ROS [2] and therefore inherits many of its useful qualities. Users of ROS, which comprises the bulk of roboticists, will find Space ROS readily adoptable. Its modularity and reusable packages will enable rapid software development, and an estimated 40% reduction in develop costs [3]. When released, the Space ROS open-source repositories will be hosted in GitHub, and therefore accessible to lunar roboticists and the space community worldwide.

There is precedent using ROS in space robotic experiments and missions, including Astrobee, Robotnaut and Valkyrie. The upcoming VIPER) Volatiles Investigating Polar Exploration Rover) mission is employing ROS on its ground node [4]. ROS, however, is not flight-quality software and is limited in its use on the lunar surface and other space missions. We are therefore taking special care to ensure the Space ROS software that lunar robotic and autonomous systems employ is flight-qualifiable. For instance, we are designing Space ROS to subscribe to strict memory management criteria, to be real-time and deterministic, and to be compatible with the processing platforms expected in robotic space systems.

Furthermore, the Space ROS team is defining a quality policy and code compliance rules to which Space ROS software will subscribe. The policy aligns to existing flight software standards including NPR 7150.2 [5]. And we are developing a continuous integration infrastructure and a suite of automated tools that enforces code quality by checking Space ROS software for compliance. The infrastructure detects and tracks non-compliance in an accessible database to allow an open community of software developers to contribute to the technical maturation of Space ROS. Moreover, the Space ROS continuous integration infrastructure catalogues software pedigree, artifacts and documentation to support the upstream qualification of a robotic mission's software.

Space ROS is a paradigm shift in how robotic flight software is maturated and maintained. Rather than customizing software per mission, Space ROS provides accessibility and reuse of quality software, continuous integration for persistent software maturation and maintenance, and an open-community of contributors and users. Our intent is that Space ROS will become the de facto software standard for robotic and autonomous systems on the moon, and beyond.

References:

[1] https://cfs.gsfc.nasa.gov [2] https://design.ros2.org [3] JPL D-26303, Handbook for Software Cost Estimation (2003) p 19. [4] N. V Patel, NASA's next lunar rover will run open-source software, April 12, 2021, MIT Tech Review [5] NASA Procedural Document NPR 7150.2C

Prototype Low-Pressure Advanced Thermal Mining System with Vapor Extraction, Ionization and Electrostatic Transportation, and Deposition of Ice in an Engineered Cold Trap

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Introduction: The ongoing "Advanced Thermal Mining Approach for Extraction, Transportation, and Condensation of Lunar Ice" project at UTEP cSETR funded under NASA LuSTR [1] is focused on the design, development and demonstration of a lab-scale advanced thermal mining prototype of 1 kg ice collection capacity that integrates engineered extraction, transportation, and desposition of water vapor from lunar regolith (Fig. 1). There are significant uncertainties in estimating the thermophysical properties of icy lunar regolith such as effective specific heat and thermal diffusivity. It is known that lunar regolith has a rather low thermal conductivity, about 0.01 W/(m·K) [1]. In contrast, the thermal conductivity of ice is over 2 W/(m·K). This indicates that the thermal conductivity of icy regolith can change over a wide range depending on the regolith/ice mass ratio. This dependence cannot be reliably predicted. Moreover, the vapor sublimates in an ultra low-pressure environment that makes it difficult to transport the rarefied vapor to the cold trap to re-capture the ice. Furthermore, the limitation of power in lunar south pole and poor thermal conductivity of deposited ice in the cold trap makes the ice re-capture system less efficient.

Therefore, this work experimentally measures the thermophysical properties of icy regolith, experimentally compares the sublimation rates at various concentrations and depths from capture tent and thermal drill technologies, and presents the design, development and demonstration of an advanced thermal mining prototype that integrates vapor ionization and electrostatic transportation to the cold trap by electrostatic field, and re-capture 1 kg of ice on the evaporator of an engineered cryogenic heat pipe.

Measuring the Thermophysical Properties of Ice: This work focuses on measuring the effective specific heat and thermal diffusivity of icy regolith at temperatures ranging from -150 C to 25 °C. A lab scale thermal excavation system will be developed in this work based on the experimental characterization of sublimation rates for thermal drill and capture tent technologies.

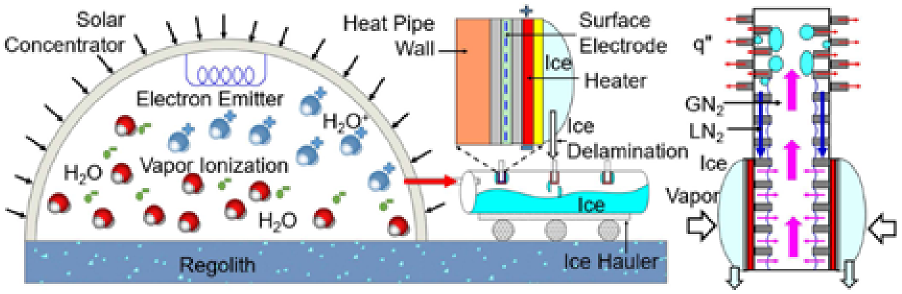

Figure 1: cSETR advanced thermal mining technology

Vaor Ionization and Electrostatic Transportation to the Cold Trap: The rarefied vapor transportation system focuses on the ionization of sublimated low-pressure vapor and transportation to the cold trap in electrostatic field. This work experimentally characterizes three ionization transport methods: (i) a tungsten filament electron emitter, (ii) a radio-frequency plasma source, and (iii) a tungsten filament with applied magnetic field for electron trapping. More than 450% increase in water collection rates has been estimated analytically based on a laboratory scale experiment using ionization transport methods.

High Capacity Cold Trap with Engineered Cryogenic Heat Pipe: This work fouces on developing a cryogenic heat pipe utilizing the micro/nano-scale surface engineering and experimentally collecting ice in cryogenic vacuum environment. Preliminary analytical studies show that 1 kg of ice can be collected in 11 hours using pulsed delamination of ice using the engineered heat pipe.

In Summary, this work develops a high capacity advanced lunar thermal mining system.

References: [1] Lunar Surface Technology Research Quarterly Progress Report, NASA Grant 80NSSC21K0768; [2] Heiken et. al., The Lunar Sourcebook: A User's Guide to the Moon, Cambridge University Press, Cambridge, 1991.

Design and implementation of the Heavy Onboard Platform for Lunar ISRU and Terrain Excavation (HOPLITE) to enable payload development and field testing for lunar and mars applications. P. van Susante, E. Cobb, A. Goddu, H. McGillivray, C. Miller, E. VanHorn, Planetary Surface Technology Development Lab, Michigan Technological University. (Contact: pjvansus@mtu.edu)

Introduction: The Heavy Onboard Platform for Lunar ISRU and Terrain Excavation (HOPLITE) is a modular robotic system built at Michigan Technological University (MTU) that enables the field testing of ISRU technologies. Many payloads are currently being designed and implemented for lunar applications and there is a need for accurate, reliable, and safe mobility of these payloads during field testing. Using a large sensor array, fine tuned control, and autonomy, HOPLITE is designed to provide a solution to this need.

Payloads: HOPLITE can incorporate a diverse range of payloads from excavators to surveying equipment weighing up to 200 kg. Mechanical, electrical, and software infrastructure was built to enable easy integration. All edges of the frame incorporate an exposed 20 mm T-slot to create a modular mounting system for payloads. To provide data and power to payloads, pass-throughs allow access directly into the rover's electronics cabinet. Payload software is compartmentalized as a ROS node and abstracted into a software library that can communicate and issue commands to necessary subsystems onboard HOPLITE. The current payload configuration is for the Planetary Surface Technology Development Lab (PSTDL) 2021 Lunar Surface Technology Research (LuSTR) grant. HOPLITE currently provides its services to a ground-penetrating radar (GPR) and will also include a percussive hot cone penetrometer (PHCP) onboard in later tests in order to field test characterization of the spatial distribution of ice within the lunar subsurface in addition to profiling the geotechnical properties of regolith.

Data Collection: To support the development of various payloads, HOPLITE uses its sensors to generate data about its own orientation, movement, electronic power system, and vision system. Onboard is a 9 degree of freedom (DoF) inertial measurement unit (IMU) in addition to a high-accuracy global navigation satellite system (GNSS). Due to its modular design, additional sensors necessary for a specific test can easily be attached and integrated into HOPLITE. The rover uses two 160 degrees field of view (FOV) cameras on the front and back and supports various cameras for payload observation with differing FOVs and resolutions. Data streams collected from all onboard sensors are consolidated into a central database onboard HOPLITE. This allows engineers to query all system telemetry at any given time throughout the duration of a test.

Ground Control: HOPLITE is controlled via a custom open-source ground control software designed by a team at the PSTDL. Extensions can be developed for all subsystems and payloads. The ground control software provides pre-defined extensions including an integrated terminal, vision capture, sensor streaming, and more to provide system control and monitoring of HOPLITE and its payloads.

Autonomy: Testing different ISRU and excavation payloads on a rover requires reliable and consistent operation. Collection passes with a GPR must be straight, and separated with enough distance, and cone penetrometer tests must be done at specific locations, spaced sufficiently apart. To this end, HOPLITE uses an autonomous system using its cameras, IMU, and GNSS to perform testing. This system is built from low-level commands, which can be chained into operations and actions. With these commands accurate, repetitive control is provided by allowing the operator to outline the behavior of the system without needing to actively direct it. The operator can dictate the rover's orientation, location, and operation of payloads directly or with a command sequence. This ensures the safe and effective operation of HOPLITE and its payloads.

FIG 1. HOPLITE driving at the Stamp Sands field testing location in Houghton, MI.

LunarNav: Lunar Rover Navigation Using Craters as Landmarks.

L. Matthies, S. Daftry, S. Tepsuporn, Y. Cheng, S. Ravichandar, D. Atha, R. Swan, H. Ono. Jet Propulsion Laboratory, California Institute of Technology, 4800 Oak Grove Avenue, Pasadena, CA, USA. (Contact: lhm@jpl.nasa.gov)

Introduction: The Artemis program requires robotic and crewed lunar rovers for resource prospecting and exploitation, construction and maintenance of facilities, and human exploration. These rovers must operate in sunlit and shadowed areas at high latitudes and must support navigation for 10s of kilometers (km) from base camps. Similarly, a lunar science rover mission concept ("Intrepid") [1] is under study that would traverse approximately 1800 km over four years at low latitudes, driving at speeds in daylight (30 cm/s) that are about 6 times faster than Mars rovers to date and doing short drives at night to maximize science productivity.

These rover mission scenarios require functionality that provides onboard, autonomous, global position knowledge ("localization"), in sunlight, shadow, and during the lunar night. However, planetary rovers have no onboard global localization capability to date; they have only used relative navigation [2], by integrating combinations of wheel odometry, visual odometry, and inertial measurements during each drive to track position relative to the start of each drive. At the end of each drive, a "ground-in-the-loop" (GITL) interaction is used to get an absolute position update from human operators in a more global reference frame. As a result, autonomous rover drives are limited in distance so that accumulated relative navigation error does not risk the possibility of the rover driving into a "keep-out zone"; in practice, drive limits of a few hundred meters are to be expected.

Technical Approach: In this work, we are developing algorithms and software to enable lunar rovers to estimate their global position on the Moon with error less than approximately 10m in sunlit areas and 15m in permanently shadowed areas. This new capability will eliminate the need for ground-in-the-loop interactions with human operators for lunar rover global position estimation, which will substantially increase operational productivity of lunar rovers and will reduce operations costs.

This will be achieved autonomously onboard by detecting craters in the vicinity of the rover and corresponding them to a database of known craters mapped from orbit. As craters are ubiquitous on the surface of the Moon, our approach is applicable everywhere, does not require high resolution stereo imaging from orbit as some other approaches do [3, 4], and has potential to enable position knowledge with order of 10m accuracy at all times.

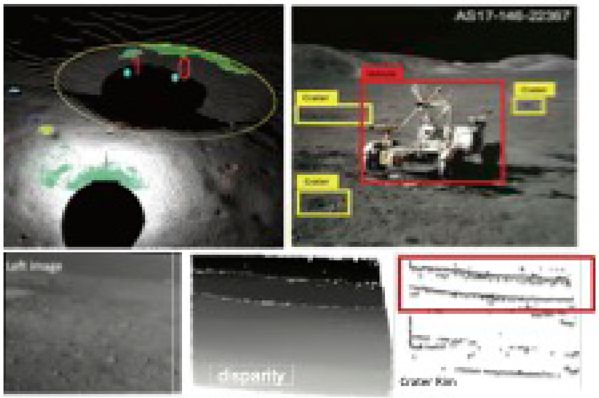

Figure 1: Examples of crater detection algorithms using different sensing modalities: **(top-left)** Uising LiDAR. The colored regions identify potential crater back walls based on point normals; numbers identify potential locations after processing; the yellow ring shows the final estimated location of the known crater landmark. **(top-right)** Using monocular images. A convolutional neural network was trained to detect craters (in yellow. Using stereo images. **(bottom)** Disparity cues were used to detect the front and back rim of the crater (in red).

The overall technical LunarNav framework consists of three main elements: 1) crater detection, 2) crater matching, and 3) state estimation. This year the focus of our work has been on the first element. We developed crater detection algorithms based on three different sensing modalities: (1) 3-D point cloud data from lidar, (2) 3-D point cloud and image data from stereo camera pairs, and (3) image appearance from monocular images using.

These algorithms were demonstrated on a dataset of both real and simulated lunar images, in a representative environment. Figure 1 shows qualitative examples of crater detection using the 3 modalities. Furthermore, performance evaluation was done as a function of varied crater sizes, distances to craters and illimunation conditions.

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Enabling Industrial Robotics Capabilities in Space. M. Day Towler[1], F. Martinez[1], and D. Anthony[1]. [1]Southwest Research Institute, 6220 Culebra Rd., San Antonio, TX 78238 (Contact: meera.towler@swri.org)

Introduction: Recent years have seen significant advancements in robotics, which is causing a proliferation of robotics across numerous industries historically not open to automation. While automotive and welding are fields with extensive investment in robotics for decades, the last few years have seen increased investments in robotics for industrial applications such as blending, excess material removal, and assembly [1].

These advances are making automation cheaper and more agile. Requiring less programming for setup allows end users to integrate robotics into their processes without the expense of a dedicated robotics department for installation and maintenance. Additionally, recent development in image processing and machine vision are making a number of industrial processes easier and more efficient. Improved automated vehicles imaging techniques are bringing efficiency and speed to machine vision for industrial robotics.

With such a wide range of highly advanced robotics capabilities available to industrial processes on Earth, the next frontier is robotics in space. Autonomy in space will enable more complex missions farther from Earth and will make space missions cheaper and more accessible.

Industrial Robotics Capabilities for Space: A few capabilities are particularly valuable to the current and future needs of the space industry. Scan-n-Plan™ identifies 3D geometries and plan paths for various industrial processes. Event-based cameras provide high-speed sparse data sets that are well suited to the limited processing power available on FPGAs.

Scan-n-Plan™

Scan-n-Plan™ technologies are a suite of software tools that are developed by SwRI under the Robot Operating System (ROS) development environment for industrial applications over the last decade.

The major components include:

- Automated calibration tools
- Scan acquisition software
- Automated tool path planning tools
- Process coverage simulation tools
- Automated robot path planning tools
- Image classification tools

These tools are deployed in numerous robotics systems, including sanding, grit blasting, chemical de-paint, power-wash, grinding, and painting.

Event-based Cameras

Event-based, or neuromorphic, cameras are a recent maturation in camera technology that produce "events" that are changes in lighting intensity on a per-pixel basis (Figure 1), at the sensor level. The events create a sparse representation of changes in an image, resulting in a much sparser representation of the environment, reducing bandwidth and processing requirements.

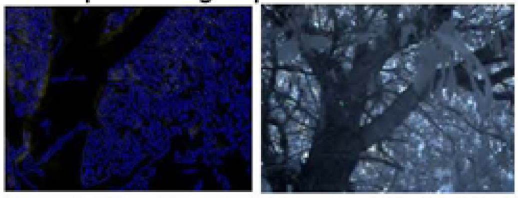

Figure 1. Event-based camera image processed to show edges (left); equivalent image from normal camera (right).

Effectively, an event-based camera compresses the information in the environment to only the changing elements at the sensor level, allowing computer vision algorithms to operate only on relevant portions of an image, as opposed to a traditional camera pipeline, where a computer must first process full resolution camera images to isolate regions of interest in an image. Additionally, because the event-based camera detects both increases and decreases in light intensity, it can detect portions of an object occluding a light source, as well as light reflecting from a target object. This increases its versatility and allows it to operate in a wider variety of lighting conditions. Moreover, event-based cameras have an extremely high dynamic range, often above 110dB, which allows them to operate in rapidly changing lighting conditions.

Conclusion: Robotics capabilities developed for Earth-based industrial processes can be used for space to enable missions farther away from Earth and make spaceflight less expensive.

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Reviewing of the existing rock engineering knowledge on the Moon rocks. DeMoraes, Roberto and Gaspari, Giuseppe, AECOM, Roberto.demoraes@aecom.com, AECOM, Giuseppe.gaspari@aecom.com. (Roberto.demoraes@aecom.com)

Between 1969 and 1972, six Apollo missions brought back 382 kilograms (842 pounds) of lunar rocks, core samples, pebbles, sand, and dust from the lunar surface. The six space flights returned 2200 separate samples from six different exploration sites on the Moon. In addition, three automated Soviet spacecraft returned necessary samples totaling 300 grams (approximately 3/4 pound) from three other lunar sites. The lunar sample building at Johnson Space Center is the principal repository for the Apollo samples. The lunar sample laboratory is where pristine lunar samples are prepared for shipment to scientists and educators. Nearly 400 samples are distributed each year for research and teaching projects. The study of rock and soil samples from the Moon yields valuable information about the early history of the Moon, the Earth, and the inner solar system. For example, we have learned that a crust formed on the Moon 4.4 billion years ago. This crust formation, the intense meteorite bombardment occurring afterward, and subsequent lava outpourings are recorded in the rocks. We review the data on the physical and mechanical properties of the lunar rocks such as basalt, anorthosite, and breccia acquired in the direct investigations on the lunar surface carried out in the human-crewed and robotic missions and in the laboratory examination of the lunar samples returned to the Earth. We consider all of the main physical and mechanical properties of the lunar soil, such as the composition, density and porosity, cohesion and adhesion, angle of internal friction, shear strength of loose soil, deformation characteristics (the deformation modulus and Poisson ratio), compressibility, and the bearing capacity, and show the change of some properties versus the depth. This review brings a new view on the Moon rock's mechanical properties, which are relevant to constructing effects on materials extraction, excavation, processing, and handling.

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High-capability, Low-mass Lunar Mobility at an Affordable Price. S. Dougherty, and D. Chavez Clemente, Maxar Space Robotics LLC, 1250 Lincoln Ave, Pasadena, CA 91103. (Contact: sean.dougherty@maxar.com)

Introduction: NASA's return to the Moon with the Artemis program is providing frequent delivery and support of payloads on the lunar surface through the Commercial Lunar Payload Services (CLPS) program. Initial landers are stationary. Some are delivering small rover payloads with limited capability. VIPER is a much more capable rover but pushes the limits of landed payload mass and does so at a higher price point.

Mobility will become a de facto science enabling capability on the moon, much as it has on Mars – but how do we make that happen within the mass and cost profile of CLPS? How do we enable mobility on every mission that would benefit from it, at the cadence CLPS plans to visit the lunar surface?

Maxar will leverage both its quarter century of leadership in planetary robotics and its recent technology developments to provide highly capable mobility at a sustainable price and mass. We will discuss our Lunar Under Actuated (LUnA) robotic appendage (arm or leg), NASA's electrodynamic dust shielding [1] incorporated in Maxar's SolarHub Lunar Vertical Solar Array system, and our in-house, high-value motor control electronics as they relate to new mobility capabilities. LUnA in particular, supported by the NASA Tipping Point program, represents an exciting step forward in planetary mobility.

The need to negotiate rugged terrain, reach a wide range of destinations, and extract a vehicle when stuck typically require a high degree of complexity and large number of actuators or degrees of freedom (DOF). Simple vehicles are lower cost and mass but have limited ability to traverse or survive the lunar night. LUnA drives multiple degrees of freedom (DOF) from a single actuator and motor located at the base, rather than equipping each DOF with its own actuator. This simple change has a number of beneficial effects: reducing and cost and mass while maintaining the capability of the system, and also improving the system performance in extreme environments. This allows it to work in difficult locations like Permanently Shadowed Regions (PSRs) of the Moon, and also allows it to more easily survive through the night to support long term sustainable operations.

We will apply our LUnA technology to deliver advanced suspension and walking capabilities, while minimizing the complexity of the control and actuation system. We will leverage our deep expertise and extensive heritage to produce a system that delivers high performance in an affordable package.

As a first step toward a fully integrated mobility platform, we have established a rover testbed for quick iteration of new concepts and technologies. Current status and results from this rover testbed, shown in Figure 1, will also be discussed. This system was designed, from the start, to be modular and scalable. Using our existing family of actuators from very small to very large, it can take the form of anything from a micro-rover sized vehicle to something as large as the VIPER or Perseverance rovers. The technology can be incorporated on existing landers or anything from two-wheeled trailers to six or eight-wheeled heavy equipment.

Figure 1- Maxar's Hybrid Iterative Testbed (HIT) for rover mobility technology evaluations.

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Microwave Structure Construction Capability Year One Accomplishments

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The Microwave Structure Construction Capability (MSCC) element, part of the Moon to Mars Planetary Autonomous Construction Project (MMPACT) was initiated in 2020. MSCC is responsible for creating horizontal and vertical infrastructure on the moon using microwave energy. Microwave energy was selected since is the only method to volumetrically heat the regolith. All other sintering/melting methods rely on thermal conduction through the very low conductivity surface, resulting in an inefficient process. Advances were achieved in materials characterization and understanding, microwave sintering in vacuum, and microwave design and analyses.

Two dielectric property testing systems have been developed at Radiance Technologies and JPL. These will examine dielectric properties at cryogenic temperatures and over a broad frequency range. Permittivity and permeability testing at -60˚C in vacuum from 0.05 to 3GHz has been generated at JPL. Additional modifications will be made to go to -190˚C (LN_2). Radiance Technologies created a test system to measure dielectric properties at greater than 10 GHz and initiated work on developing a vacuum capable, portable test system to measure dielectric properties of Apollo regolith and simulants from 100 MHz to 18 GHz. These tests are to identify optimal heating frequencies and protocols.

During microwave sintering at about 1100˚C, volatiles were creating difficulty in achieving a reasonably dense specimen. Due to processing in vacuum and the nature of the lunar regolith, some volatiles and porosity are expected. However, the Earth produced simulants have non-lunar materials in them that create volatiles that aren't representative of lunar regolith. Therefore, a five month effort was conducted to establish a heat treat method to remove these non-lunar materials. Tests were conducted using TGA mass spectrometry, heating in vacuum and conducting mass spectrometry, dielectric and DTA, Raman, BET, particle size analysis, morphological analysis, carbon and sulfur chemical content determination and microscopy. The process has been scaled-up to 6 kg batch size and undergoing evaluation. A 36 kg batch size is the target for JSC-1A and other limited availability simulants. These calcining protocols will be standard for NASA and beyond.

MSCC has also created scalable processes for fabricating synthetic lunar materials. Processes to fabricate Anorthite (plagioclase $CaAl_2Si_2O_8$), Diopside (pyroxene $CaMgSi_2O_6$), and Enstatite (pyroxene $Mg_2Si_2O_6$) have been generated. These materials will enable generation of microwave sintering models to bound various composition ranges anticipated on the Moon, therefore mitigating the need for a precise simulant with respect to location on the Moon.

Successful microwave sintering in air using a horn applicator was demonstrated. All previous microwave vacuum sintering in the literature was at small scale and in a contained enclosure thus taking advantage of reflections. This is the first to use a lunar like microwave applicator to sinter ceramic in a bed as it would be done on the Moon. Small scale and inert sintering was conducted to assist in developing protocols with quicker turnaround times than larger scale testing. Testing has anchored thermal analysis predicting heat flow in vacuum during microwave sintering. Thermal conductivity testing was also initiated.

Microwave coupling to the regolith has been modeled by multiple organizations and with different software packages. At least six horn designs and applicator configurations for both magnetron and solid state sources are being examined. Optimal simulant container designs for microwave have also been generated. The power and electronics design for the solid state microwave system has been initiated. Concept designs for a lander based microwave sintering have been evaluated.

GEODETIC SIGNATURES OF ACTIVE LUNAR TECTONICS

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

Introduction: The lunar surface is often assumed to be entirely static, except for tidal deformations and meteorite impact; a recent study using Lunar Laser Ranging (LLR) constrains the relative motion of the Apollo 11 and 14 retroreflector arrays to be no more than 4 mm/yr over a 14-year period [1]. However, the seimometers left on the Moon by the Apollo astronauts as part of the Apollo Lunar Surface Experiments Package (ALSEP) arrays revealed that there were relatively strong surface or near-surface lunar moonquakes [2], which must be associated with ground motions. Twenty-eight such Earthquakes were detected in eight years of observation, and the largest were energetic enough to present a possible risk to Astronauts on the surface in the seismic zone [3].

Active Thrust Faults on the Moon: Recent work has shown a connection between at least some of the surface moonquakes and geologically young thrust faults on the Moon, with 7 of the 28 ALSEP events been within 60 km of an apparently young lobate scarp. Conventional crater-size / frequency dating indicates that these lobate scarps are <50 Myr old [4]. Another study [5] shows that geologically young lobate scarps and wrinke ridges are assocated with fresh boulder fields (Figure 1), with large numbers of 1 to 10 meter boulders on top of or beside ridges in the fault area. The rapid destruction of such boulder fields by meteorite impacts indicates that these areas must be very young (< 10 million years in some cases). The combination of fresh faults with the apparent creation of boulder fields strong suggests that at least some surface moonquakes are associated with meter level surface motions (as multiple small motions would not unearth or create large numbers of meter sized boulders on top of ridges). A veritical or horizontal displacement of such a size on the near side of the Moon could be easily observed by either LLR of retroreflectors, or Very Long Baseline Interfermetry (VLBI) of suitable radio beacons [6], respectively, assuming that a suitable geodetic network was placed in the seismically active area.

Penetrator Deployed Geodetic Arrays: Ballistic penetrators can support lunar science by allowing for the rapid creation of instrument and communications arrays on the lunar surface, including deployement of a geodetic network together with seismometers in a tectonically active area [7, 8, 9, 10].

Space Initiatives Inc (SII) is developing a standard instrument package including a three axis accelerometer, three axis magnetometers, geophones and COMPASS VLBI Beacons to enable their accurate global positioning on the lunar near-side [6]. Such an array, with current deployment mechanisms, would allow instrumentation of roughly a 1 km wide section of an active thrust fault in a single mission, possibly in conjunction with a NASA CLPS lander. By providing cm-level determinations of local fault motions, the fault could be monitored (and fault motions compared to local seismology) even in the absense of large moonquakes on the instrumented fault. Such a mission would also be able to better constrain the seismic risk of such areas.

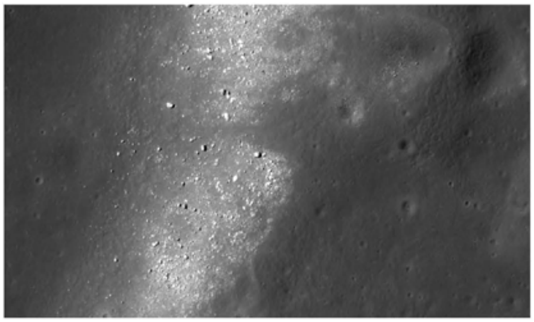

Figure 1: Boulders in a candidate area for recent lunar tectonics in Mare Nubium. Portion of LROC NAC image M1144863959L; North is up.

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Overview of the Volatiles Investigating Polar Exploration Rover. T. Fong[1], B. Bluethmann[2], and L. Bridgwater[2]. [1]NASA Ames Research Center, Moffett Field, CA, [2]NASA Johnson Space Center, Houston, TX. (Contact: terry.fong@nasa.gov)

Introduction: The Volatiles Investigating Polar Exploration Rover (VIPER) is a lunar volatiles detection and measurement mission. VIPER will be launched to the Moon in late 2023 as a payload on the Commercial Lunar Payload Services (CLPS) flight provided by Astrobotic's Griffin lander. The VIPER rover is a solar powered, mobile robot designed to traverse up to 20 km during a mission lasting up to four lunar days.

After landing in a south polar region, the VIPER rover will travel to investigate a range of Ice Stability Regions (ISRs) across scales from 100s of meters to kilometers and conduct surface and subsurface assessment of lunar water and other volatiles. VIPER includes a suite of rover-mounted instruments (three spectrometers and a drill), which the VIPER science mission team will use to characterize the nature of the volatiles and to create global lunar water resource maps.

Mission Objectives: While the existence of lunar volatiles has been known since the Apollo era, it is only during the last 20 years that the extent and form of these volatiles has been better understood. It now appears likely that economically significant amounts of water ice may exist at the poles of the Moon, however, the distribution, physical state, and accessibility of this water is still not sufficiently characterized to determine if it would provide an economically viable resource for a variety of uses.

To evaluate the potential for lunar polar volatiles to be utilized, VIPER has two primary objectives: (1) Characterize the distribution and physical state of lunar polar water and other volatiles in lunar cold traps and regolith to understand their origin; and (2) Provide the data necessary for NASA to evaluate the potential return of In-Situ Resource Utilization (ISRU) from the lunar polar regions.

Rover Design: VIPER is a four-wheeled planetary rover with active suspension (Figure 1). Active suspension provides capabilities including changing vehicle ride height, traversing comparatively large obstacles, and controlling load on the wheels. All-wheel steering enables the vehicle to point arbitrarily while roving, e.g., to keep the solar array pointed at the sun while in motion. The offset steering combined with active suspension improves driving in soft soil.

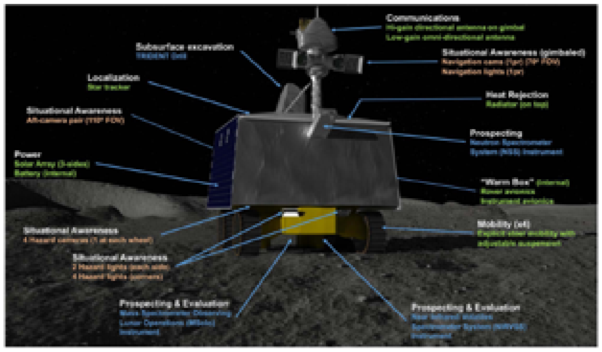

Figure 1. The VIPER planetary rover includes a prospecting and evaluation payload for lunar volatiles, navigation sensors, power and thermal management, and Direct-to-Earth communications.

The VIPER rover's software is split between onboard Rover Flight Software (RFSW) and off-board Rover Ground Software (RGSW). RFSW runs onboard the rover on radiation hardened (RAD 750) and radiation tolerant (AiTech SP0-S) avionics. RFSW utilizes NASA's Core Flight System and provides low-level hardware interfaces, basic mobility control, waypoint driving, odometry, basic error checking, and device/payload services. RGSW runs at mission control on Earth using commodity desktop computing. RGSW is implemented as an ensemble of Robot Operating System 2 (ROS2) nodes and performs navigation, mapping, and generation of rover driver decision support data.

The VIPER rover is electrically powered and relies upon batteries and three approximate 1 m^2 solar arrays (one each on the port, starboard, and aft surfaces). The rover operates with Direct-to-Earth (DTE) communications using an omni-directional low-gain / low-bandwidth antenna and a steerable high-gain / high-bandwidth antenna. Eight cameras, including a stereo pair mounted on a pan/tilt gimbal are used to support remote driving. An inertial measurement unit, star tracker, and joint encoders provide data for localization, attitude, and body rate estimation.

During surface operations, the rover follows a specific surface traverse plan, primarily by teleoperation via individual position (waypoint) commands set several meters ahead of the vehicle. The rover operates with constant DTE communications while in the Sun and in shadows (for short periods of time).

AUTONOMOUS ROBOTIC PLATFORMS TO PROVIDE ACCESS TO EXTREME LUNAR ENVIRONMENTS. A.J. Gemer[1], J.A. Cyrus[1], F. Meyen[1], and J.B. Cyrus[1], [1]Lunar Outpost, Inc. (17700 S. Golden Rd., Ste 102, Golden CO 80401, AJ@lunaroutpost.com)

Introduction: Robotic assets on the lunar surface are advancing rapidly, providing increased opportunities for scientific and commercial payloads to engage with the lunar environment in ever more interactive ways. However, limitations imposed by communications availability, thermal and lighting conditions, and topography may impact the availability of teleoperation-type controls for many robotic assets, especially mobile assets (rovers). Thus, varying levels of autonomy are employed to mitigate risks and develop optimal CONOPS for Lunar Outpost's Mobile Autonomous Prospecting Platform (MAPP) line of lunar rovers.

Mission 1 (M1) MAPP will be launched in late 2022 to provide lunar surface mobility to technology demonstration payloads, in particular, proving out communications infrastructure to enable future, large-scale missions to the lunar South Pole. As M1-MAPP is intended to survive a single lunar day, it is imperative that MAPP's mobility capabilities are utilized efficiently and near-continuously for the duration of the mission. A photo of a TRL 6 MAPP technology demonstrator during CONOPS field testing is shown below in Fig 1.

Figure 1: M1-MAPP / COLD-MAPP

For the M1-MAPP mission in late 2022 and a follow-on mission in 2023-2024, site-specific CONOPS analysis is well underway. This includes examination of the communications availability, solar incidence (and related thermal conditions), terrain shadowing, and hazards of the planned MAPP traverses. These analyses have revealed areas where full teleoperation of MAPP will be challenging. M1-MAPP is solar-powered, and the lighting conditions near the lunar south pole are highly dynamic and change drastically over the duration of the mission. Additionally, local terrain features near the landing site may impact the RF communications propagation, reducing comms bandwidths in areas of good solar illumination and further constraining optimal paths of travel.

Autonomous navigation, path planning, and hazard avoidance offer versatile tools to address rover traverses through low-comms areas. Were M1-MAPP relying solely on human-in-the-loop teleoperation, an area of sufficiently reduced communications bandwith would present an impassible barrier, limiting mission range and potential objectives. In situations where the optimal path, from a solar illumination standpoint, brings M1-MAPP into an area of reduced communications, automated waypoint driving may be used to plot a course through the area and back into a higher-comms area on the other side; autonomous hazard avoidance, characterized on representative obstacles in lunar testbeds on Earth, allows M1-MAPP to determine the lowest-risk path while navigating through the area. In this way, M1-MAPP offers greater versatility in dynamic, extreme environments than a teleoperated rover.

For future missions, these autonomy capabilities will extend MAPP's range to include excursions into even more extreme areas, such as permanently-shadowed regions or underground environments. NASA has funded Lunar Outpost to develop MAPP into the Cryogenic-Operation, Long-Duration MAPP (**COLD-MAPP**), a 15kg rover platform designed to survive one or more lunar nights. As COLD-MAPPs have substantially longer mission durations, they can drive up to 20km, further increasing both the need for and the application of capable autonomous operation. To enable PSR exploration, additional thermal management technologies may be mounted within some of MAPP's internal payload bays, creating the **PSR-MAPP**. Swarm operations of multiple MAPP rovers also benefit from MAPP's autonomous navigation capabilities; a single human operator may control the objectives and operations of the swarm at a high level, while leaving the path planning and hazard avoidance tasks to the individual rovers. COLD-MAPP will be mission-ready in early 2022, with PSR-MAPP following shortly thereafter.

Planetary Construction 3D Printing Using In-situ Resources and Mission Recyclables. I. Giwa[1], D. Moore[1], M. Fiske[2], A. Kazemian[1], [1] Louisiana State University, 3319 Patrick F. Taylor Hall, Baton Rouge, LA 70803, [2]Jacobs Space Exploration Group, Huntsville, AL, 35806. (Contact: kazemian1@lsu.edu)

Abstract: Space exploration is a key aspect of human colonization of the Moon and Mars in the future. In preparation for the NASA Artemis mission and a subsequent challenging journey to Mars, temporary or permanent structures like habitats, research labs, landing pads, hangars, and shield structures are necessary for the survival of astronauts and protection of assets and equipment. Such supporting infrastructure are central to the successful coordination and completion of space exploration missions in extreme environments such as the Moon and Mars. Lack of atmosphere, microgravity, cosmic radiations, micrometeorites, dusty terrains, and significant thermal fluctuations present a high risk to unprotected humans and a variety of exploration and research equipment which are needed for comprehensive Lunar and Martian exploration. Construction 3D printing (C3DP) is large-scale additive manufacturing technique which could be used for fabricating habitats and other infrastructure needed to support these manned or unmanned missions on the celestial bodies. Extrusion-based C3DP is a robotic construction technology that holds great potential for automated planetary construction using in-situ resource utilization (ISRU) based materials. Constraints associated with the cargo payload of Space Launch Systems (SLS) limit the number of terrestrial construction materials that can be transported to the Moon and Mars. Therefore, ISRU offers a viable solution for manufacturing construction materials out of indigenous raw materials. The scarcity of readily available construction materials or the high-energy demand for processing extraterrestrial resources into needed construction materials highlight the importance of investigating the use of mission recyclables as another possible option for space construction. Materials like metals and polymers can provide the possibility of recycling and being reused as construction materials for sustained planetary construction. This paper presents a review of the performance, potentials, and challenges of ISRU based materials that can be harnessed and processed as the printing material for extrusion-based construction 3D printing. Furthermore, this paper also explores the prospect of using recycled and recovered ISRU based materials for a sustainable extraterrestrial construction process. Finally, some preliminary results and experimental results are presented on the characterization of ISRU-based printing materials to assess their flowability and extrudability, printability, and buildability.

Space Environmental Effects for Exploration. E. G. Hayward[1] and M. K. Nehls[2], [1]NASA Marshall Space Flight Center, EM41, MSFC, AL 35812, [2]NASA Marshall Space Flight Center, EM41, MSFC, AL 35812. (Contact: erin.g.hay-ward@nasa.gov)

Introduction: NASA Marshall Space Flight Center's Space Environmental Effects (SEE) Team enables a wide variety of missions and projects to meet their science and exploration objectives by proving materials and systems in relevant extreme environments. The SEE Team has the capability to simulate many different space environments including lunar and planetary, LEO to HEO, and deep space. Our combined effects facilities can simultaneously expose materials to high vacuum, UV/VUV radiation, solar wind plasma (electron and proton radiation), temperature extremes, and planetary surface and regolith effects.

SEE testing allows systems and subsystems to be validated and demonstrated in relevant space environments, identifying problems earlier in development, and raising Technology Readiness Level to TRL-6. Combined testing in a single facility not only lowers cost compared to using multiple facilities, but gives truer results due to synergistic effects. The SEE Team works with customers to define the specifications of the environment where they will be operating, and designs a test that meets their specific goals and requirements. We measure and characterize properties such as optical and electrical changes in coatings, mechanical properties degradation, subsystem thermal performance, and spacecraft charging.

Recent tests that have enabled human and robotic exploration of our solar system, include:

- Europa Clipper - internal charging; electrostatic discharge/arcing on cables and coatings; instrument testing in Venus fly-by environment
- Europa Lander - irradiation of solid rocket motor propellant, with our unique ability to handle energetic materials.
- Parker Solar Probe - validation of the Solar Probe Cup in the High Intensity Solar Environment Test facility
- NESC ISS RPCM Safety Assessment - ensuring astronaut safety on EVA by looking at the effects of arc-generated molten metal on spacesuit material
- E-Sail - Development of a system for making the first laboratory thrust measurements for an electric solar wind sail design, enabling unique mission profiles

With NASA's return to the lunar surface, the SEE Team is increasing the capabilities to test effects of planetary body surfaces. We intend to supplement our existing LETS (Lunar Environment Test System) to allow for testing with a wider variety of lunar and Martian regolith simulants and atmospheric gases.

Lunar Avatar – a model-mediated 'store-and-forward' approach to telerobotic operations.

C. A. Hibbitts[1] and the APL Lunar Avatar Team, [1]JHUAPL, 11100 Johns Hopkins Rd., Laurel, Md. 20723 (Contact: karl.hibbitts@jhuapl.edu)

Introduction: The Lunar Avatar team at the Johns Hopkins Applied Physics Laboratory has over the past year demonstrated the feasibility of model-mediated, 'store-and-forward' telerobotic operation on the surface of Moon. Instead of using images or video for situational awareness, the operator interfaces with the robot through a 3D model [1]. 'Model-mediated' refers to the interface where an operator controls a virtual representation, and that model sends commands to the robot. Then the model is updated based on sensor feedback from the robot (the mediation). The use of an immersive, mixed-realtiy (XR) model in lieu of still images enables the development of a 3D database allowing interaction with the robot latency free (between updates) in an otherwise latent environment. Also, operation is possible in both 1st and 3rd person for improved efficiency in three areas in particular: Operations & Science Backroom; Interacting with and Manipulating the Environment such as through arms; and directing motion (Mobility). A Boston Dynamics Spot quadruped robot and a commercial off-the-shelf (COTS) point cloud sensor provided interface information for an operator using MRET and Unity software packages. A 3-second uplink and 3-second downlink delay simulated latency as if operating the Lunar Avatar from Earth through a relay satellite.

Operations & Science Backroom. The team utilized Spot as if it were an astronaut. The operator communicated with a "CapCom" that also interfaced with a science backroom (Figure 1), typical of operations during Apollo and again used in simulated astronaut operations such as Desert RATS [e.g., 2]. This proven operational structure results in rapid and efficient operations. With the ability to record and review operations in the XR environment, it is also feasible to verify actions as intended before executing. The concurrent development of the database furthermore enables the operator, or 'other astronauts', to immersively explore the lunar surface that has previously been mapped, such as for identifying areas of science and exploration interests to which the Lunar Avatar can be directed again for a more detailed follow-up. These combinations of capabilities lead to increased operational cadence.

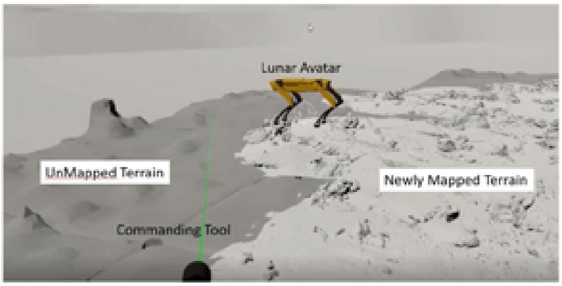

Figure 1. VR headset view of Lunar Avatar Operator.

Mobility & Manipulation of the Environment: We operated Spot in a sandy environment loosely analogous to the lunar surface, demonstrating the ability to direct the robot to a specific location. Spot's on-board low-level autonomy was effective at executing commands in the presence of hazards. Separately, an operator used robotic arms to perform complex tasks such as picking up rocks, rotating them, and positioning a spectrometer to obtain infrared reflectance spectra, all under a comm-delayed environment, demonstrating the value-added of reviewing/playing back the recorded planned motion in the XR environment, for verifying the activity before executing (Figure 2).

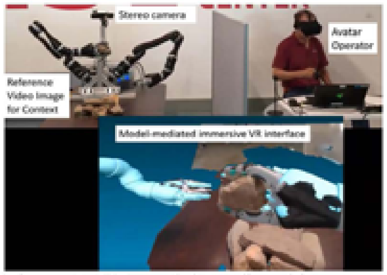

Figure 2. VR model-mediated immersive operation of arms, with a 6-second roundtrip comm latency added.

Summary: The Lunar Avatar project at APL has demonstrated the potential feasibility of model-mediated telerobotic operation of assets on the Moon, controlled from locations where latency would otherwise be prohibitive to telerobotic operations. With further maturation, model-mediated telerobotic operations should be considered as a near-term solution to complex lunar surface operations, enabling such needed capabilities as construction, excavation, and outfitting as well as surface science and exploration.

References: [1] P. Mitra and G. Niemeyer. Intl. J of Robotics Research, 27(2):253-262, 2008.; [2] Bell Jr, E. R., Badillo, et al. (2013). *Acta Astronautica*, *90*(2), 215-223.

ISPACE'S 2022 MISSION AND FUTURE COMMERCIAL CAPABILITIES FOR LUNAR SCIENCE MISSIONS.

K. Acierno[1] and K. O'Neill.[1] | [1]ispace technologies U.S. Inc., 3001 Brighton Blvd., Suite 153, Denver, CO 80216, kyle.acierno@ispace-us.com

Introduction:

The advent of the Commercial Lunar Payload Services (CLPS) program and the maturation of lunar exploration more generally is providing revolutionary access to the lunar surface for landed science missions. The Lunar Surface Innovation Consortium (LSIC) has previously recognized the value of international and commercial partners and encourages the sharing of information between commercial industry and academia.

ispace Background:

ispace inc. endeavors to expand humanity's economic sphere beyond Earth by discovering and utilizing resources on the Moon. Utilization of lunar resources, particularly water ice, will be crucial to the economic development of cislunar space and enabling further human exploration to the Moon, Mars and beyond.

Over the past five years, ispace inc. has significantly expanded its global presence. In addition to further expanding our headquarters in Tokyo, ispace is proud to have created major subsidiaries in Luxembourg and, as of 2021, the United States.

M1 & M2 Update

First, our presentation will update the global space community on progress made towards ispace's M1 and M2 missions facilitated by the Series 1 lander currently undergoing assembly and integration in Tokyo and Germany The presentation will provide an overview of the key science objectives accomplished by our upcoming missions and illustrate the payloads that will be flown to Lacus Somnorium and the Lunar South Polar regions

Novel Capabilities Provided by the Series 2 Lander

Next, we will describe advancements of ispace's lunar program, showcasing advancements in lander and rover design. Specifically, the presentation will detail ispace inc.'s expanded presence in the United States and the plans for our advanced lunar lander program, termed "Series 2" which will feature significantly greater capability compared to existing offerings.

Series 2 is designed to deliver payloads to both lunar orbit and the lunar surface. The lander has a payload design capacity to deliver up to 500kg[i] to the lunar surface. For missions where payloads are exclusively for lunar orbit, capacity can be substituted to deliver up to 2,000kg[ii] to orbit. It has a modular payload design with multiple payload bays, allowing for flexibility and optimization for a wider range of government, commercial and scientific customers. Notably, the lander aims to be one of the first commercial lunar landers capable of surviving the lunar night and is designed to have the ability to land on either the near side or far side of the Moon, including polar regions.

We intend to present how our U.S.-based advanced lander program will facilitate future landed science missions and advanced mobility options for the planetary science community

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[i] Commercial payload sales mass and revenue will be mission dependent.

[ii] Commercial payload sales mass and revenue will be mission dependent.

Rocket Mining System to Extract Lunar Water. Matthew Kuhns, Vice President of Research and Development at Maten Space Systems, 1570 Sabovich St, Mojave, CA, 93501, mkuhns@masten.aero.

Introduction: Usable as drinking water, rocket fuel, and other vital resources, lunar ice is critical to maintain a sustained presence on the Moon and allow future missions to Mars and beyond. It can also be used in conjunction with other volatiles found in lunar regolith, such as oxygen and methane, to support energy, construction, and manufacturing needs. Masten's new method for a Rocket Mining System would enable rapid, reliable, and ongoing extraction of lunar ice and volatiles located at the Moon's polar and permanently shadowed regions.

How it works: Masten teamed up with Honeybee Robotics and Lunar Outpost to design a new Rocket Mining System that can rapidly extract frozen volatiles from the Moon. This method disrupts lunar soil with a series of rocket plumes that fluidize ice regolith by exposing it to direct convective heating.

It utilizes a 100 lbf rocket engine under a pressurized dome to enable deep cratering more than 2 meters below the lunar surface. During this process, ejecta from multiple rocket firings blasts up into the dome and gets funneled through a vacuum-like system that separates ice particles from the remaining dust and transports it into storage containers.

The small, low mass system, including the rocket fuel, engine, collapsible dome, and storage containers, can be attached to a rover and delivered to the Moon on Masten's lunar landers. The system is projected to mine up to 12 craters per day and produce 100 kg of ice per crater. That would allow us to recover more than 420,000 kg of lunar water per year.

How it's different: Unlike traditional mechanical excavators, the rocket mining approach would allow us to access frozen volatiles around boulders, breccia, basalt, and other obstacles.

Most importantly, it's scalable and cost effective. Masten's system doesn't require heavy machinery or ongoing maintenance. The stored water can be electrolyzed into oxygen and hydrogen utilizing solar energy to continue powering the rocket engine for more than five years of water excavation. This system would also allow us to rapidly excavate desiccated regolith layers that can be collected and used to develop additively manufactured structures.

As one of the first commercial companies sending a lunar lander to the Moon, Masten is in a unique position to deploy this system. We've been testing plume surface interactions with our reusable rockets and engine test stands for more than a decade. The tests we conduct have allowed us to collect cratering data using a frozen lunar regolith simulant at our facilities in Mojave.

These experiments helped us understand what triggers different cratering effects and subsurface gas permeation. It also provided the groundwork we needed to ensure optimal pressure conditions in the dome and maximize excavation on the Moon.

A Dual-Pin Tool Coupler for Robotic Excavation.

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Introduction: Excavation and construction on planetary surfaces would benefit from a dust-tolerant tool *coupler*, to let a robot easily swap out robust end-of-arm *tools* such as a heavy excavation bucket, rock ripper, material extruder, gripper, or powered rock breaker. We built and robotically tested several approaches for robot-to-tool couplers, and recommend a dual-pin coupler for standard use on robots and tools.

Prior Work: On the International Space Station (ISS), robot arms use derivatives of the Flight Releasable Grapple Fixture (FRGF), a long mating pin with a three-lobed mechanical contact surface [1]. This is sturdy and flight-proven in orbit for decades, but it is heavy, and not shown to be dust tolerant for surface operations.

A lighter coupler is the ISS-derived wedge mating interface (WMI), although the wedges may jam or bind if covered in dust.

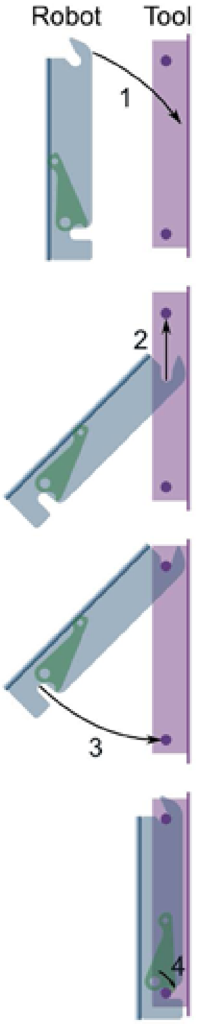
Robotic tool changers [2] are often low force but also low mass (<1kg) and low stack height.

Our dual-pin system is scaled down from the Cat® Pin Grabber [3], Yanmar Quick Coupler, or Miller PowerLatch excavator attachment systems. These field-proven designs use large clearances (>3mm) to allow reliable operation even when covered in dust, and thick steel parts make them robust to years of jobsite use with 100 kN forces.

Coupler Requirements: Flight hardware should be minimal mass. Surface mining and construction operations require a robust tool coupler, capable of handling large forces and moments. Robotic operation requires simple rapid attaching and detaching in dusty environments. Alignment precision is less important, due to the inherently low precision of excavation operations.

Tool Coupler	*Mass / tool*	*Dust Tolerance*	*Ease of Coupling*	*Force*
Dual-pin	0.4 kg	Field derived	Good, one pin at a time	>500 N
ISS WMI	4 kg	Wedge may jam	Wedge self-aligns	500 N
FRGF	8 kg	LEO design	Proven automation	667 N

Dual-pin Coupler: We propose putting two parallel pins on the tool. On the robot a static top hook self-aligns the coupler and tool, and a powered locking lug clamps the other pin in the bottom slot, to securely lock the tool to the robot. This puts all the active parts on the robot, and minimizes the mass of the tool. Four degrees of freedom are constrained by direct contact, and the tool pitch is constrained by the locking lug, leaving only minimal sliding motion along the pins.



Coupling: To attach to a tool, the robot's end effector **approaches** the tool tilted down (1) so the robot's top hook enters the tool between the pins. After making contact the robot then **lifts** up until the top pin is captured (2) by the top hook. The robot then **tilts** the coupler until its bottom slot captures the tool's bottom pin (3), optionally using gravity to align the tool to the top hook. The robot can then **clamp** the tool's bottom pin (4) by tilting the locking lug. Detaching is in the reverse order.

Dimensions: For robot or tool around 100kg, 8mm diameter pins of length 75mm, mounted 125mm apart and 15mm from the face of the tool, works well. We tested this with a robot and a variety of tools: buckets, fluid tank, powered rockbreaker, robot deployment hanger. Upside down mating also works. Built from steel, the tool side masses under 400g and handles forces over 500N. Electrical connections could be made centrally or below the bottom pin. Computer vision markers for automated coupling could be applied above the top pin or at either side. A double-size version with hollow 16mm pins allows tools to also be lifted by human hands in gloves, which could allow shared robotic or human manipulation of tools or containers.

References: [1] ISS MCB, International External Robotic Interoperability Standards (IERIS), Feb. 2018. [2] Gyimothy D. and Toth A. (2011) *IEEE/ASME Advanced Intelligent Mechatronics (AIM)* pp. 1046-1051. [3] Caterpillar Tech. Spec. for Cat Pin Grabber Excavator Couplers, GEJQ9387.

Open source, open standards, and collective invention in the space industry. J. Woods and C. McMahon, Open Lunar Foundation, 399 Webster Street, San Francisco, CA, 94117. (Contact: juno@translunar.io)

Introduction: Collective invention occurs when free exchange of information enables rapid technological advance, and differs from individual invention and commercial invention (e.g. research and development). In an academic context, one example of collective invention is the open science movement. In the for-profit world, nominal competitors may work together on key infrastructure, called pre-competitive collaboration.

Normally, the products of these efforts are eventually privately recaptured, but the free/libre and open source software (FLOSS) movement has created a legal mechanism to prevent that recapture. Moreover, collective invention is often a product of specific engineering cultures or participant ideologies. Silicon Valley engages in pre-competitive collaboration by producing open source infrastructure as a foundation for proprietary, closed source innovations; however, space industry collaborations are much rarer.

We briefly review advantages and disadvantages of FLOSS, open hardware, and open standards. We discuss key barriers in the aerospace industry, as well as potential motivators for renewed participation, and make recommendations based on interviews conducted with anonymous space industry executives and several years of experience running open source projects.

Background: While the commercial space industry relies extensively on collective invention (e.g. academic and NASA research and development, as well as substantial tech industry infrastructure), it contributes back much more rarely than the tech industry. While there exist a large number of successful FLOSS projects in the space industry, most are primarily government or academic in origin and support. The culture of the open source movement has existed independently of the legal mechanism, having inherited much from its origins in the academic open science movement.

Pre-competitive collaboration: Explicit in the term ‘pre-competitive’ is that such collaborations revolve around non-differentiators (those technologies that help businesses compete against others in the economic niche are known as differentiators). An example of pre-competitive collaboration is the open consortium model, as demonstrated in the GENIVI Alliance, which produced a Linux-based platform for in-vehicle entertainment, and publishes a variety of open standards. GENIVI was founded in 2009 between auto industry competitors including OEMs such as BMW, Honda, and Hyundai, as well as other supply chain participants like Clarion, Bosch, LG, Garmin and Nvidia. The space industry would greatly benefit from similar open consortia.

Economics of open source: To be adopted broadly, FLOSS projects must nearly always be coded and well documented with reuse in mind. In studies on closed source software, building in reusability entails an up-front cost (~2–5x), but produces a positive return-on-investment within a few years; moreover, the cost of integrating components written with reuse in mind is a fraction of the cost of writing new components.

Incentives for collaboration: Commercial entities considering open source business models ought to consider not only the existing market but how to facilitate the existence of a future market. Organizations working outside of low-Earth orbit would benefit more from actions that increase the market size than from finding customers among the currently extremely limited market.

We stand at an inflection point in the growth of the commercial space industry. The cultural norms at space industry companies today will shape the norms and laws of the societies we build in space.

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A Robot Factors Approach to Designing Modular Hardware.

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Introduction: For space hardware that would be needed to support a Lunar habitat, even routine maintenance tasks typically require a coordinated sequence of complex bimanual motions. Few robots are capable of the dexterity and fine motor control needed to execute such tasks. Rather than relying on highly sophisticated robots, a "robot factors" approach [1] instead promotes autonomy by designing hardware to be easily manipulable by typical robot platforms and end effectors. Here, we outline the design principles that informed the redesign of a power module, and demonstrate its operation by a 6 DoF robot arm.

AMPS: NASA's Advanced Modular Power Systems (AMPS) project seeks to standardize future space power system architectures by using a modular approach [2]. All modules conform to a standardized form factor, but provide different functions (e.g., Bi-Directional Converter, Load Switchgear Module, etc.). Removing and replacing modules is a two-handed dexterous operation (a fingernail or small screwdriver may even be required to unlock wedge-locks). Module replacement is not suited to current NASA robots.

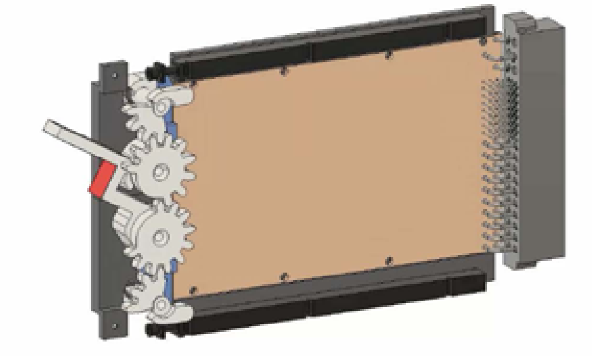

Fig. 1: The redesigned power module uses a gear assembly to coordinate different types of motion output from the single input (supplied by the robot moving a lever along a 120° stroke). For insertion, the first 90° causes the injectors to press against tabs in the chassis, mating the 47-pin connector at the rear of the module with the corresponding connector attached to the chassis. The remaining 30° engages wedge-locks that tighten against the chassis, locking the module into place. For ejection, these steps are reversed.

Robot Factors: Previous work has recognized the value of designing hardware specifically to facilitate robot manipulation, using the terms "robot factors" [1] and "robot ergonomics" [3]. However, this work has not demonstrated robotic operation or quantitative performance analysis.

Design Principles: The most important redesign feature consolidates compound motions into simple mechanisms, using a gear system (Fig. 1). The design also incorporates filleted corners and edges to enforce correct alignment of the module. While planning for robot operation, a key concern was to avoid the workspace boundaries and joint limits, where accuracy and power are reduced.

Fig. 2 shows a 6-DoF robot arm demonstrating removal and insertion of a power module (making full electrical mating between the connectors). The simple mechanical advantage afforded by the longer lever reduces the torque requirement to fall within the robot's specified range.

In future work, we expect that the "Robot Factors" approach, and a similar design, could be applied to other hardware like filtration systems.

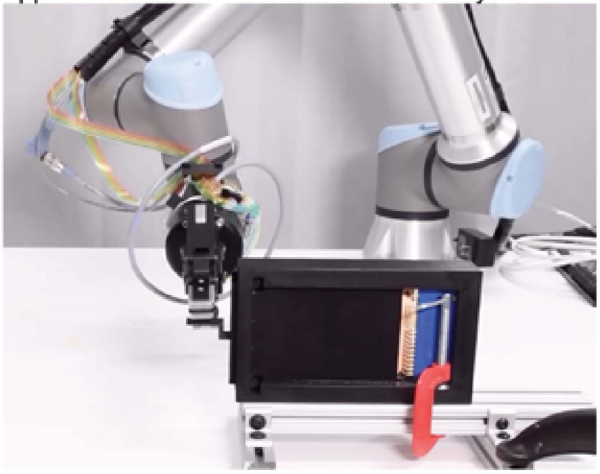

Fig. 2: A 6 DoF robot arm with a standard parallel-jaw gripper is able to autonomously insert a module, mate its connectors, and lock it into place with the simple input motion of pivoting a lever.

References:

[1] W. C. Chiou and S. A. Starks "An Introduction to the Concept of Robot Factors And Its Application to Space Station Automation", Proc. SPIE 0580, 1985.

[2] Advanced Modular Power Systems (AMPS), NASA. https://techport.nasa.gov/view/10759

[3] R. Sosa et al., "Robot Ergonomics: Towards Human-centered and Robot-inclusive Design", Proc. 15th Intl. Design Conference, 2018.

An International Lunar Resource Prospecting Campaign.

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Introduction: Lunar resources that could be useful for sustaining humans on the Moon (and potentially for export off-Moon) have been known to exist for years. However, understanding them and their use in enabling science, human exploration, and a vibrant cislunar economy remains rudimentary at best. We define the critical next step for understanding lunar resources that could build science, exploration, and commercial synergies.

Resources vs. Reserves: This semantic yet critical distinction is crucial in understanding the full scientific, exploration, and commercial potential of lunar resources. The USGS [1] defines resources and reserves as follows: **Resource**: a con- centration of naturally occurring solid, liquid, or gaseousmaterials in or on the crust in such form that economic extraction of a commodity is regarded as feasible. **Reserve**: That portion of an identified resource from which a usable mineral or energy commodity can be *economically and legally* extractedat the time of determination.

The term "resource" in a lunar context has been used interchangeably with "reserve", which has caused confusion. Based upon current knowledge and likely users, the only potential lunar reserve is oxygen from regolith as it is present in about the same proportion anywhere on the Moon. However, defining it as a "reserve" requires the economic and legal issues to be addressed.

Economics: The reserve definition implies that the resource can be extracted, refined, transported, and used at a profit (i.e., the value of the products is more than the cost of acquiring the products). This has not been achieved for any lunar resource because only the United Launch Alliance has placed a value on lunar-derived water (for rocket fuel) at $500/kg [2,3]. At this time, a true market value for any lunar resources has not been established so their economic potential cannot be evaluated.

Legal Implications: The Outer Space Treaty (OST) [4] has been interpreted to indicate use of lunar resources is prohibited or severely restricted. For example, **Article I** states: "*The exploration and use of outer space, including the Moon and other celestial bodies, shall be carried out for the benefit and in the interests of all countries*". **Article II** further states: *Outer space, including the Moon and other celestial bodies, is not subject to national appropriation by claim of sovereignty, by means of use or occupation, or by any other means.* However, **Article III** states: "*States Parties to the Treaty shall carry on activities inthe exploration and use of outer space, including the Moon and other celestial bodies..., in the interest of maintaining international peace and security and promoting internationalco-operation and understanding*". An International Lunar Resource Prospecting Campaign would therefore be compliant with the Outer Space Treaty.

The Artemis Accords [5] establishes a common vision viaa set of principles/guidelines/best practices for the governance of civil exploration/use of outer space to advance the Artemis Program. Space resources are highlighted where the signatories:

- *note that the utilization of space resources can benefit human kind by providing critical support for safe & sustainable operations;*
- *emphasize that extraction & utilization of space resources be executed to comply with the OST & in support of safe & sustainable space activities;*
- *commit to informing the Secretary-General of the United Nations as well as the public and the international scientific community of their space resource extraction activities in accordance with the OST;*
- *intend to use their experience under the Accords to contribute to multilateral efforts to further develop international practices and rules applicable to the extraction and utilization of space resources, including through ongoing efforts at the COPUOS.*

An International Lunar Resource Prospecting Campaign (ILRPC): An ILRPC is needed to understand the full economic potential of the Moon and comply with [4]. This has begun in an ad hoc fashion with the ISECG member missions to the lunar south pole to explore volatile deposits [6], but extensive cooperation be-tween nations is lacking. This could be initiated either by the Artemis Accords or the ISECG, building on the work ofLEAG [6]. Encouraging such international collaboration in lunar prospecting, international diplomacy is promoted. History shows us that international cooperation in space leadsto an enduring program (e.g., ISS), whereas competition doesnot (e.g., Apollo). An ILRPC allows countries to participate in this exploration, regardless of economic status. Countries could contribute instruments, launch vehicles, rovers, etc., to ensure the same datasets are obtained for each site identified by orbital data (e.g., [7]). By sharing data obtained from this campaign (which will inform science, exploration, and commerce), commercial companies (& space agencies) will understand the reserve potential of lunar resources, such that a true market valuecan be determined and the reserve potential fully evaluated into the future.

Such an approach requires organization, integration, and coordination at the highest level. The current organization of Artemis is through mission directorate cooperation via a federated board. If this model is used, the integration needed for the ILRPC campaign will be subject to the traditional inefficiencies of stove-piping that is endemic at NASA. Therefore, **Artemis** needs to become a **Program** and have a position above the directorates at the Administrator/Deputy Administrator level to avoid stagnation. The **Artemis Program** will require a leader who can integrate the relevant pieces from the mission directorates, thus avoiding any "turf wars". Establishing the ILRPC through the Artemis Program office would encourage international partners to team with NASA, maybe through the Artemis Accords or other avenues, but international and commercial on-ramps to the ILRPC should be built in from the beginning. This approach would allow lunar resources to be, for the first time, considered as essential for establishing a permanent human presence on the Moon and kick-starting the cislunar economy that would benefit society here on Earth.

References: [1] USGS. (1980) *Geological Survey Circular 831.* [2] Sowers G. (2016) *Space Policy 37*, 103-109. [3] Sowers G. (2018) *Space Journal #3(17)*, 8-13. [4] United Nations (1966) *Outer Space Treaty.* [5] NASA (2020) *The Artemis Accords.* [6] LEAG-ISECG Volatiles SAT 2 Report (2017). [7] LEAG (2015) Volatiles SAT Report.

Low Cost Robotics for Lunar Science and Exploration. A. M. Qureshi, Maxar Space Robotics LLC, 1250 Lincoln Ave, Pasadena, CA 91103. (Contact: atif.qureshi@maxar.com)

Introduction: Maxar is a proud partner in NASA's return to the moon and in excited to enable the timely and important lunar science needed to accomplish this. Maxar Space Robotics has been a leader in robotic systems and mechanisms for a variety of extra-terrestrial applications for almost 25 years. We will present and discuss our latest efforts, relating to operations and science on the lunar surface, and aligned with all the LSII focus areas.

While NASA's Commercial Lunar Payload Services (CLPS) program has successfully reduced the cost and increased the frequency of lunar surface access, there is still a need for similar improvements in robotic manipulation systems. These are critical for science payloads that require positioning and pointing capabilities removed from the lander, or that require direct contact with the lunar surface. They are also crucial to support long term sustainable infrastructure development in support of exploration goals. Maxar Space Robotics is pioneering low cost lightweight lunar robotics and is investing in advanced technology to deliver revolutionary capabilities in the near future.

SAMPLR: The SAMPLR mission features our low cost modular robotic architecture. This mission will demonstrate techniques necessary for In Situ Resource Utilization (ISRU) and excavation. We have developed a right-sized and readily reconfigurable robotic system, composed of simple and mature components. These are readily available at reasonable cost and lead time, allowing the manipulator to be customized to a particular missions needs and then delivered quickly and within a constrained budget. The first flight unit of this robotic arm system will be delivered in late 2021 for integration with the lander. SAMPLR will be landing at the Lunar South Pole in 2023.

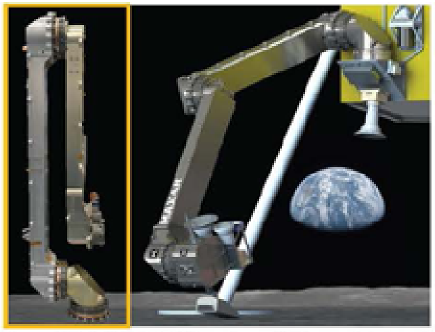

Figure 1 – SAMPLR Mission (R) and Engineering Model (L)

LUnA and SolarHub: We are partnering with NASA to develop the Lunar Under Actuated (LUnA) robotic arm, as well as the SolarHub Lunar Vertical Solar Array system. LUnA is being supported by the NASA Tipping Point program, and represents a revolutionary leap forward in space robotics, driving all the manipulator joints from a single actuator and motor located at the base, rather than equipping each joint with its own actuator. This simple change has a number of beneficial effects: reducing and cost and mass while maintaining the capability of the robotic system, and also improving the system performance in extreme environments. This allows it to work in difficult locations like Permanently Shadowed Regions (PSRs) of the Moon, and also allows it to more easily survive through the night to support long term sustainable operations. LUnA will minimize cost and mass impact on a mission, and also provide advanced robotic capabilities such as sample packing and stowage, and payload swap out (for multi-instrument science).

On SolarHub, Maxar will apply Electrodynamic Dust Shielding (EDS) to mitigate the effects of Lunar dust. This technology has been under development at Kennedy Space Center (KSC) for many years and has reached a high level of maturity. The SolarHub project will adapt it to provide dust protection to rotary actuators and other moving mechanisms, paving the way for its application on robotic manipulator systems.

Figure 2 – LUnA Concept with Cutaway View (L) and SolarHub (R), which will adapt KSC EDS Technology

Enabling Autonomous Lunar Surface Robotics with Artificial Intelligence. K. V. Raimalwala[1], M. Faragalli[1], M. M. Battler[1], and M. Cross[1]. [1]Mission Control, 162 Elm. St. W., Ottawa ON K1R 6N5, Canada, kaizad@missioncontrolspaceservices.com

Introduction: As commercial missions to the Moon pave the way for near-term efforts to establish permanent infrastructure, it is well understood that the lunar economy should grow increasingly self-reliant in contrast to Earth-centric missions that have been the norm so far. Similar to ISRU goals to use resources in situ, self-reliant mission architectures must increasingly use on-site computing to enable real-time autonomous robotics with AI applications. This is critical for these reasons:

1. Communications latencies of up to 10 seconds round-trip make real-time operations that rely on Earth-based decision-making unfeasible.
2. Communications drop-outs can be expected or unexpected due to technical or environmental circumstances. In either case, robotic and crewed architectures can benefit from on-site computing to process and store data and provide actionable insights for real-time decisions.
3. Communications data transfer constraints. The data pipeline between the Moon and the Earth is constrained, and returning high-volume data to process on Earth for supporting real-time operations is not feasible. While this pipeline is expected to grow, so will the ecosystem of lunar spacecraft that use it.

Flight Demonstration of Supporting Lunar Surface Robotics with AI: In 2022, Mission Control will demonstrate an Edge Computing approach to support navigation for the Rashid micro-rover in the Emirates Lunar Mission led by the Mohammed Bin Rashid Space Centre (MBRSC) [1]. Our AI technology, integrated on the lander, will extract operationally relevant information from images streamed back from Rashid.

This demonstration will highlight how distributed computing can augment the autonomy of spacecraft systems that are otherwise designed to rely on Earth-based operations teams for certain tasks, paving the way for autonomous lunar surface infrastructure development.

The primary investigation will demonstrate the feasibility and usefulness of automated terrain classification for science and navigation operations using deep learning models embedded on a compact and high-performance flight-ready processor that may be integrated on the mission's lander spacecraft. The classifier will identify high-level surface features in images from the rover's navigation camera and downlink the outputs to science teams, to be used in rapid terrain assessment for science and navigation decision-making. This is targeted to be the first demonstration of Deep Learning on a lunar mission, unlocking potential applications for autonomous decision-making in future missions.

In addition to AI-based terrain classification, Mission Control will lead investigations in trafficability estimation, path planning, and power modeling for skid steer vehicles. The data from Rashid will be used to train the terrain classifier, whose outputs can then be used to intelligently estimate rover wheel slip hazards and power consumption.

Supporting Lunar Excavation & Construction Activities: To enable efficient uncrewed excavation and construction activities, vehicles and other systems must operate to a high degree of supervised autonomy as direct tele-control is unfeasible due to communications latencies and possible drop-outs. Ideally, Earth-based operators can uplink high-level objectives that these systems can parse to identify and execute tasks [2]. Any autonomous system executing tasks in the domain of lunar excavation and construction must also be able to understand its environment and the objects they are interacting with, known in robotics terms as 'perception'. This is essential to support safe and efficient task planning and execution. The state of the art in perception techniques involves using computationally intensive deep learning models to identify patterns and extract knowledge from sensor data such as camera images [3]. For example, an outfitting machine that outfits structures with cabling and other components must be able to identify the objects it works with, the geometry of its working space, and ideally also whether a task was successful or if it induced any problems.

Our demonstration of using AI on the lunar surface can enable these algorithms for scene reconstruction, object identification, hazard classification, and other perception capabilities, to support autonomous robotics systems in lunar infrastructure development.

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NASA'S IN SITU RESOURCE UTILIZATION TECHNOLOGY AND MISSION PLANS.

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Introduction: The National Aeronautics and Space Administration (NASA) has been directed to send astronauts back to the lunar surface and begin a sustainable human lunar exploration program in the 2020's, and to lead the first human exploration mission to the Mars surface in the 2030's. A major objective of NASA's Moon to Mars exploration program is to understand and characterize the resources that exist at these destinations, and to learn how to utilize these resources for sustained human exploration and the commercialization of space. This ability, commonly known as *In Situ* Resource Utilization (ISRU), involves any hardware or operation that harnesses and utilizes local resources to create products and services for robotic and human exploration. The NASA ISRU program is focused on the production of mission consumables and commodities to enable sustained human exploration, such as rocket propellants, life support consumables, fuel cell reactants, feedstock for manufacturing and construction, and nutrients for food and plant growth. In particular, propellants make up a significant fraction of the mass launched from Earth, are critical to mission success, and can reduce the cost for reusable transportation. Important for enabling long term surface stays and greater independence from Earth are the abilities to perform construction and manufacturing from in situ-derived materials to create and expand on the infrastructure and reduce the logistical resupply needed for sustained surface and space operations. To achieve these ISRU capabilities, NASA is developing technologies and systems, and initiating missions that will find, measure, and harness the resources of the Moon and Mars for science, human exploration, and eventually commercial space advancement. This endeavor is led by NASA's Space Technology Mission Directorate (STMD) in coordination with the Science and Human Exploration and Operations Mission Directorates (SMD and HEOMD).

Lunar Resources for ISRU: For simplicity, lunar resources under consideration for ISRU are divided into two broad categories: regolith and water/volatiles found in permanently shadowed regions (PSRs) of the lunar poles. Lunar regolith can be divided into two broad categories as well: highland and mare types, with potential additional (lower concentration) constituent resources such as pyroclastic glasses, KREEP (potassium, rare earth elements, and phosphorous), and solar wind implanted volatiles. Regolith at the lunar polar regions is primarily highland-type regolith, which is mostly Plagioclase (Anorthite) and extremely iron-poor. Both highland and mare type regolith are great resources for oxygen and metals; oxygen is over 40% by weight (wt%) in lunar regolith minerals (mostly silicates).

While orbital data provides clues about the possible water and volatile resource content and distribution in the PSRs, the only 'ground-truth' data that exists today is from the analysis of the plume created by the Lunar Crater Observation and Sensing Satellite (LCROSS) impact in 2009. The LCROSS plume (analyzed by A. Colaprete) was estimated to have 5.5 wt% water (+/- 2.9%) and lower concentrations of other volatiles such as hydrogen, carbon monoxide, hydrogen sulfide, ammonia, and others. Spectral modeling by Li (2018) shows that some ice-bearing pixels may contain ~30 wt % ice mixed with dry regolith.

ISRU in Human Lunar Exploration: NASA's human lunar exploration program, known as Artemis and led by HEOMD, is a multi-phased robotic and human exploration activity. The initial phase is primarily aimed at sending the first women and first person of color to the lunar south pole, with the goal of achieving this by 2024. This phase of exploration also includes orbital and surface robotic missions for science, technology development, and resource assessment. The next phase of human lunar exploration is aimed at demonstrating and building capabilities for longer duration lunar surface exploration missions, and to demonstrate technologies, capabilities, and operations that will be needed for the first human mission to Mars. This phase will include the use of unpressurized mobility platforms, robotic and human science tools and experiments, payload offloading and deployment systems, and initial surface power, habitat, and pressurized mobility assets. Throughout the initial phase and into the next, a major objective for ISRU is the assessment, characterization, and mapping of the lunar resources, especially the water/volatile resources in the PSRs, and demonstrating critical technologies for production of oxygen, water/fuels, and feedstock for manufacturing and construction.

Oxygen and Water Mining Strategies: Oxygen (and metals) in lunar regolith and water and other volatiles in PSRs provide both benefits and risks for developing and incorporating ISRU systems into future human missions. Water is an amazing resource and product, but there are currently significant unknowns on the form and concentration. Water can be used on its own for crew and radiation shielding or can be converted into oxygen and hydrogen for propulsion, power, and chemical processing. Regolith is plentiful in oxygen and metals, but regolith is extremely abrasive and processing it requires a lot of energy. Oxygen can be used

Design of a volumetric additive manufacturing system for in-space manufacturing. T. Schwab[1] and J. Toombs.[2], [1] Undergraduate Research Intern, 2055 Center Street Berkeley CA 94704, [2]PhD Candidate, 2521 Hearst Ave., Berkeley CA 94720. (Contact: tristanschwab@berkeley.edu)

In-Space Manufacturing (ISM) will enable NASA's long-term objective to live on the lunar surface and beyond. ISM is a paradigm shift in the creation of components, artificial organs, and space architectures. Previous AM systems aboard the International Space Station (ISS) have demonstrated commercially viable components and successful bio-prints in microgravity; however, potential disadvantages of these printers may include downtime for cleaning and maintenance, power efficiency, automation capability, and space requirements. These metrics are compared with a Computed Axial Lithography (CAL) based printer named SPACECAL. The design of SPACECAL, an apparatus containing five consecutive CAL printers, is discussed. CAL is capable for ISM as a print is produced in a sealed vial of photopolymer with minimal mechanical motion or extrusion interface, enabling a diverse portfolio of compatible resins and no shear stresses on the material. Automation techniques to produce parts in microgravity, are discussed. To evaluate the potential of CAL for ISM, the SPACECAL system will be tested by fabricating polymer components and hydrogel extracellular matrices during a parabolic microgravity test flight in early 2022.

Keywords: volumetric additive manufacturing, lithography, NASA, in-space manufacturing, microgravity

Unitized Regenerative Fuel Cells. B. M. Warrensfeltz, R. C. Utz, and T. I. Valdez, Teledyne Energy Systems Inc. (10707 Gilroy Road, Hunt Valley, MD 21031) thomas.i.valdez@teledyne.com

Introduction: Current spacecraft supporting aerospace and aeronautics missions may survive a Lunar night by implementing the following solutions: a radioisotope power source (RPS); a radioisotope heating source (RHU); power beaming; or maximization of solar irradiance exposure to the spacecraft. The multi-mission radioisotope thermoelectric generator (MMRTG) powering the Curiosity and Perseverance Rovers on Mars is a good example of a RPS which could enable spacecraft to survive a Lunar night. The Jade Rabbit Rover demonstrated Lunar night survivability with RHUs [1]. Lastly, as will be employed on the Volatile Investigating Polar Exploration Rover (VIPER), mission planners will guide this spacecraft to maximize exposure to solar irradiance during exploration [2]. In the case of a spacecraft not employing a RPS, batteries and power beaming would typically be used to supply any energy required for operation when solar irradiance is not available [3].

Discussion: A limitation of a RPS powered spacecraft would be mission cost. RPS are typically reserved for flagship missions. They may also require specific restrictions when operating in the presence of humans. RHUs would share similar restrictions as RPSs; however, their limitation is more specific to operations. Power beaming is being developed for future Lunar missions, its limitation is in mission planning and operation. Lastly, even advanced batteries would be too heavy to provide the energy required to enable Lunar night survivability for most spacecraft. An energy storage system which can enable Lunar night survivability will break new ground in science.

A unitized regenerative fuel cell system (URFC) concept has been developed as shown in Figure 1. This URFC will be comprised of intermediate temperature membrane electrode assemblies (MEAs) which operate between 100 to 240 °C. This temperature allows the URFC to operate passively on single phase reactants. The URFC will generate hydrogen and oxygen reactants from water during a charge cycle and then consume these reactants to regenerate water during the discharge cycle. In our proposed URFC, we will combine the oxygen and water tank enabling us to reduce the system volume by almost a third as compared to traditional RFCs. The proposed URFC is at a technology maturation of TRL 2.

Conclusion: Providing a power source which enables the survivability of a Lunar night will increase the science a mission can generate. This could be done at a fraction of the cost required by using a RPS. Lastly, this technology is compatible with solar, as well as power beaming technologies. As a URFC would produce heat during a discharge cycle, a portion of this heat could be provided to the spacecraft during night-time operations. This capability may also enable simplified operations while supporting science during traverses in shadowed Lunar regions.

This paper will review the advantages of a URFC for CLPS landers, mobility platforms, and Class D missions. Special attention will be given to the maturation pathway required to make this technology flight ready.

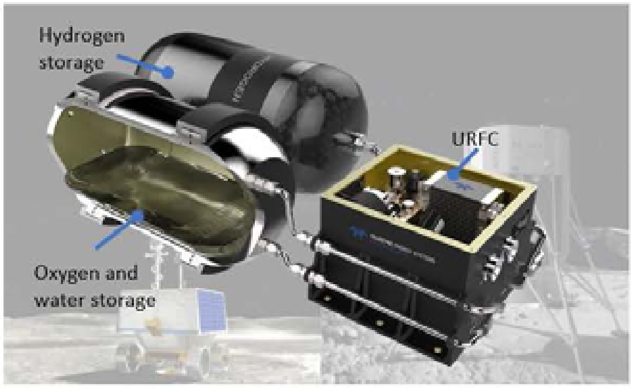

Figure 1: Intermediate Temperature Unitized regenerative fuel cell

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Radiation Hardening of Silicon Carbide Power Devices for Lunar Applications.

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Introduction: High-voltage DC buses are essential to obtain power efficiencies needed for electric vehicles on the lunar surface. Currently the target power bus voltage is around 1000 V or greater. Silicon carbide transistors can easily achieve this voltage and much higher for power converters in the terrestrial environment, but in space are susceptible to single-event burnout (SEB) and single-event leakage current (SELC) degradation because of solar and galactic energetic ions on the lunar surface. An SEB event is a permanent failure of the power device and a possible short on the power bus. The SELC events are small permanent increases in the leakage current that over time lead to significant off-state leakage current that exceeds the manufacturer specification and impacts the power converter efficiency.

Statement of Problem: The SEB and SELC effects are typically plotted with the device bias under radiation on the vertical axis, and the linear energy transfer from the ion on the horizontal axis (LET, in units of MeV/mg/cm^2), as shown in Fig. 1. The figure illustrates that the SEB boundary is well below the rated voltage of the various devices shown, on the order of 0.3 to 0.4 of the rated voltage. Consequently the full capability of the devices cannot be currently used in space. However, the SEB boundary does seem to scale somewhat with the voltage capability of the device, e.g., the 3300 V MOSFET has a significantly higher boundary than the 1200 V MOSFET, and may be used as the prototype for obtaining a device with an SEB boundary greater than 1kV.

Previous Research Effort: The majority of this research team participated in a NASA Early Stage Innovation (ESI) grant exploring the impact of radiation on silicon carbide devices from 2017 through 2019. We achieved several advancements that should contribute to developing SiC power device technology that will survive the harsh radiation environment to be encountered on the Lunar surface.

Statement of Work: The NASA LuSTR 2020 SiC program is focused on developing a radiation-hardened MOSFET survivable at 600 V minimum and a radiation-hardened diode survivable at 1000 V, while maintaining useful electrical specifications. This effort will leverage the efforts from the NASA ESI program. As noted above, using a higher rated breakdown voltage device provide substantial increases in SEB tolerance when compared to lower rated devices.

Consistent with the observation that higher voltage rated SiC parts tend to have higher SEB boundaries, the core activity in this project is first to measure the SEB performance of GE SiC high voltage MOSFETs and diodes rated at 1.7kV and 3.3 kV. The initial ion-beam experiment will be with existing GE parts. After the measurement, GE and VU will work together to determine measures that can harden the parts. The GE team will then fabricate new 3.3 kV devices modified to improve their radiation hardness. At the end of the fab cycle, the VU team will measure the hardness of the hardened parts at the same heavy-ion accelerator test facility. Both SELC and SEB will be characterized.

Additionally, failure analysis (inspection of the device/die for material property changes during radiation) has been limited to date, particularly for ion-induced degradation in which the device is still functioning. The goals of the LuSTR program are to advance the state of the art in understanding the SEB tolerance of higher rated devices, the magnitude and frequency of ion-induced degradation, and fundamental material changes due to radiation.

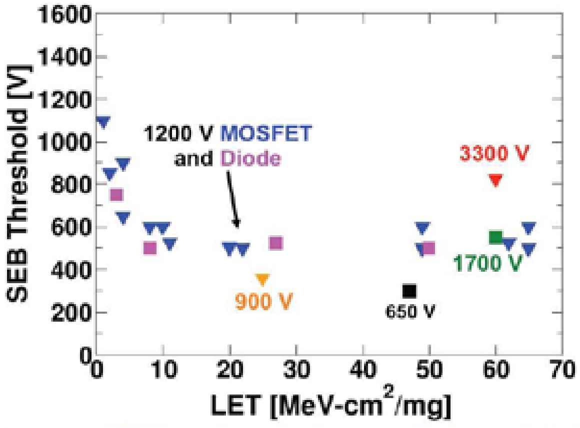

Fig. 1. An SEB boundary plot for several different SiC diodes and MOSFETs.

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REBELS: Rapidly Excavated Borehole for Exploring Lunar Subsurface. K. Zacny, J. Palmowski, L. Stolov, K. Bywaters, Honeybee Robotics, 2408 Lincoln Ave, Altadena, CA 91001 (kazacny@honeybeerobotics.com).

Introduction: The depth of lunar subsurface exploration has been limited to 3 m: this is the depth of the three lunar cores captured by Apollo 15, 16, and 17. Soviet Luna 24 sample return mission drilled to 2 m, while Chang'e 5 to 1 m. Future missions such as PRIME1 and VIPER are limited to 1 m depth.

Understanding the stratigraphy on the 10 m scale in the mid-latitude and polar regions would significantly enhance our understanding of the gardening as well as volatile distribution.

REBELS: Rapidly Excavated Borehole for Exploring Lunar Subsurface (REBELS) is a Coiled Tubing drilling system designed for penetrating >10 m below the surface. It is based on Honeybee Robotics RedWater drill, currently under development for penetrating 25 m on Mars, LISTER – a 3 m pneumatic drill scheduled to fly to the Moon in 2023 (Mare Crisium), and 2025 (Shodinger basin), and SMART drill under development for the RESOURCE project.

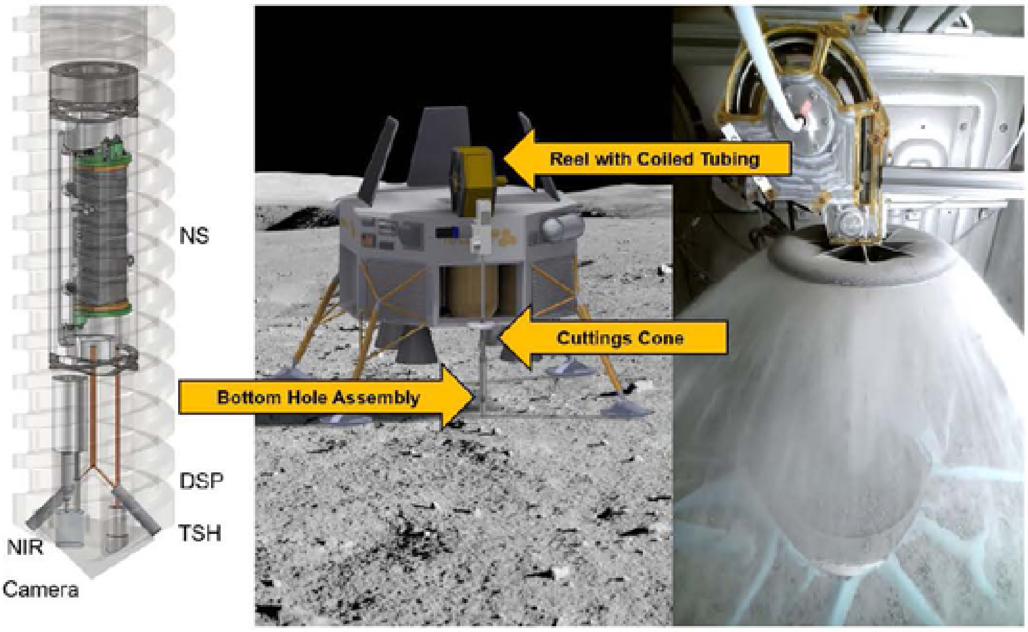

Figure 1. REBELS mounted on the lander

REBELS coiled metal tubing is reeled out from a drum and re-formed into a straight tube. The end of the tube includes the Bottom Hole Assembly (BHA). The BHA consists of a Drilling Subsystem (motors, drill bit etc.) as well as a Sensing Subsystem with the following instruments:

- Near Infrared Spectrometer (NIR):
  - Volatiles, Mineralogy
- Neutron Spectrometer (NS):
  - Hydrogen (water)
- Temperature Sensor and Heater (TSH)
  - Temperature, Thermal conductivity → Heat flow
- Dielectric Spectroscopy Probe (DSP):
  - Electrical properties
- Camera:
  - Surface texture
- Drill telemetry
  - Subsurface strength, Water content (wt. %), Water-ice physical state

The drill uses a mechanical drill bit to cut into the formation and compressed gas to blow the cuttings to the surface. The coiled tubing acts as a conduit for the wires, fiber optics and gas.

The main advantage of REBELS is to bring the instruments to the sample – i.e., all the instruments in the BHA can be activated real time and take subsurface data during drilling.

In addition, the cuttings being blow out of the hole can be analyzed real time and also collected for analysis by onboard instruments.

Various subsystems of REBELS are currently being developed to TRL ranging from 4 to 6.