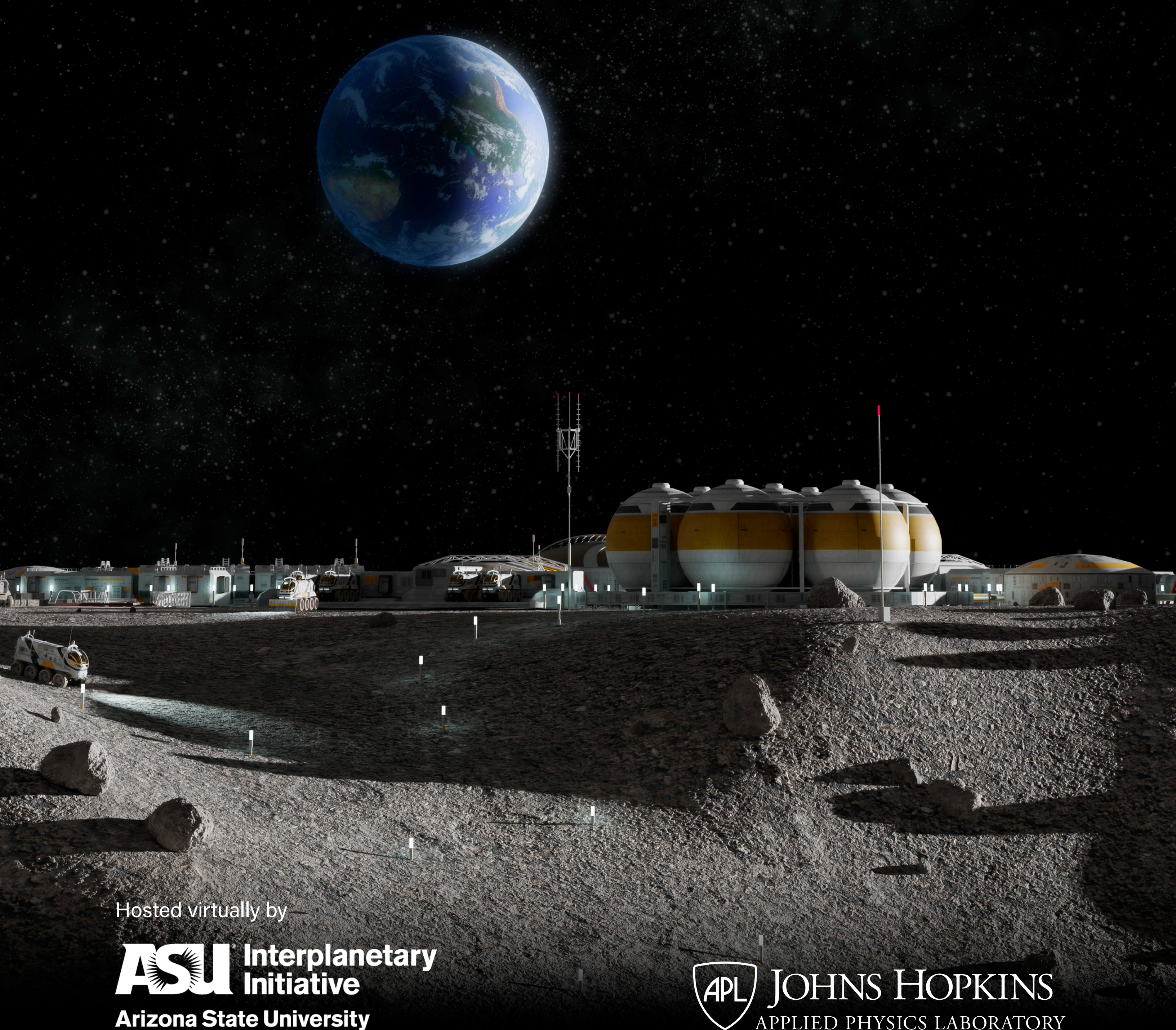
Lunar Surface Innovation Consortium (LSIC)

Fall Meeting Program

October 14–15, 2020



Hosted virtually by

ASU Interplanetary Initiative
Arizona State University

APL Johns Hopkins
Applied Physics Laboratory

Technical Organizing Committee

Joshua Cahill, Johns Hopkins University Applied Physics Laboratory
Athonu Chatterjee, Johns Hopkins University Applied Physics Laboratory
Lindy Elkins-Tanton, Arizona State University
Wesley Fuhrman, Johns Hopkins University Applied Physics Laboratory
Carol Galica, NASA
Michael Goryll, Arizona State University
Benjamin Greenhagen, Johns Hopkins University Applied Physics Laboratory
Karl Hibbitts, Johns Hopkins University Applied Physics Laboratory
Mojdeh Khorsand, Arizona State University
Rachel Klima, Johns Hopkins University Applied Physics Laboratory
Qin Lei, Arizona State University
Jorge Núñez, Johns Hopkins University Applied Physics Laboratory
Jaime Sanchez De La Vega, Arizona State University
Angela Stickle, Johns Hopkins University Applied Physics Laboratory

LSIC Summary

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

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

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

Agenda
Day 1 – Wednesday, October 14, 2020 (All times EDT)

11:30 AM	Welcome and Introduction	Michael Ryschkewitsch Space Exploration Sector Head, Johns Hopkins Applied Physics Laboratory (APL)
		Lindy Elkins-Tanton Managing Director, Arizona State University (ASU) Interplanetary Initiative
11:45 AM	Keynote Address; Artemis Update	Jim Bridenstine NASA Administrator
12:15 PM	Lunar Surface Innovation Initiative Update	Jim Reuter NASA Associate Administrator for Space Technology
12:40 PM	Integrating Technology to Accelerate a Sustainable Lunar Presence	Ben Bussey LSII Lead, APL
12:55 PM	LSIC Update	Rachel Klima LSIC Director, APL
1:30 PM	**Lunch Break**	
2:15 PM	Arizona State University Overview	Lindy Elkins-Tanton Managing Director, Arizona State University (ASU) Interplanetary Initiative
2:40 PM	ASU Feature	Michael Goryll Professor, ASU School of Electrical, Computer and Energy Engineering
3:00 PM	**Break**	
3:10 PM	Space Tech Opportunities: Panel Discussion Moderated by Mason Peck	
		Chris Baker Program Executive, NASA Small Spacecraft and Flight Opportunities
		Jason Derleth Program Executive, NASA Innovative Advance Concepts
		Jenn Gustetic Program Executive, NASA Small Business Innovation Research & Small Business Technology Transfer Programs
		Amy Kaminski Program Executive, NASA Prizes and Challenges
		Jan Rogers Technical Integration Lead, STMD Space Technology Research Grants Program
4:10 PM	Technology Transfer	Dan Lockney Program Executive, NASA Technology Transfer Program
4:25 PM	Lightning Talks	Selected Participants
4:50 PM	**Break – Transition to Poster and Networking Session**	
5:00 PM	Posters and Networking Session	
6:00 PM	**Adjourn**	

Agenda
Day 2 – Thursday, October 15, 2020 (All times EDT)

11:00 AM	Welcome & Overview of Day 2	Rachel Klima LSIC Director, APL
11:15 AM	NASA Space Technology Gaps	Niki Werkheiser NASA Space Tech, Lunar Surface Innovation Initiative Lead Mark McDonald Chief Architect, NASA Space Tech
11:45 AM	Power Panel: System Level Concerns & Current Status Moderated by Wes Fuhrman and Michael Goryll	
		Anthony Calomino NASA Space Tech, Nuclear Systems Portfolio Manager
		Marija Ilic Senior Research Scientist, Massachusetts Institute of Technology, Institute for Data, Systems, and Society
		Isik Kizilyalli Associate Director for Technology, Advanced Research Projects Agency – Energy (ARPA-E)
		Chuck Taylor NASA Space Tech, Lunar Vertical Solar Array Technology Project Manager
12:30 PM	**Break/Transition**	
12:40 PM	Scenario 1: 2028-2030 Timeframe Establishing a Sustained Presence	9 Parallel Sessions, ASU and APL Chairs
1:40 PM	**Break/Transition**	
1:50 PM	Scenario 2: 2024-2026 Timeframe Building Towards Sustainability	9 Parallel Sessions, ASU and APL Chairs
2:50 PM	**Break/Transition**	
3:00 PM	Scenario Out Brief Preparation: Discussion and Synthesis	3 Parallel Sessions, ASU and APL Chairs
4:00 PM	**Break/Transition**	
4:10 PM	Scenario Report Out Discussion and Next Steps	LSIC Group Representatives Rachel Klima, APL
5:00 PM	**Adjourn**	

Speakers

Jim Bridenstine

NASA Administrator

Jim Bridenstine was nominated by President Donald Trump and confirmed by the U.S. Senate as the 13th Administrator of the National Aeronautics and Space Administration. As administrator, he has led NASA in advancing American aeronautic, science, and space exploration objectives since April 23, 2018.

Under Bridenstine's leadership, NASA launched its new human lunar exploration mission, the Artemis program. As announced by Vice President Mike Pence in March 2019, the Artemis program will land the first woman and the next man on the surface of the Moon by 2024, the first human landing since the end of NASA's Apollo missions in 1972. Through the Artemis program, NASA is developing the Orion crew capsule and the Space Launch System, the most powerful rocket ever built. These state-of-the-art systems will help build the Gateway, a lunar orbiting space station that will give American astronauts more access to the surface of the Moon than ever before. As directed by President Trump, all lunar exploration efforts under Artemis are designed to prove our technology and perfect our capabilities to live and work on a different world in preparation for a future crewed mission to Mars.

Bridenstine has managed the continued commercial resupply of the International Space Station and has led agency efforts to partner with American businesses on the Commercial Crew Program. This program seeks to once again launch American astronauts on American rockets from American soil, something not done since the end of the Shuttle program in 2011. Additionally, Bridenstine established the Commercial Lunar Payload Services Program to partner with private enterprise in landing rovers on the lunar surface. These rovers will contain tools and science experiments in preparation for the arrival of American astronauts.

During Bridenstine's tenure, the agency has reinforced aeronautic development of the X-59, a quiet supersonic aircraft, and the X-57, the agency's first all-electric airplane. He has also backed NASA's aeronautical innovators to develop the Unmanned Aircraft Systems Traffic Management to facilitate the safe use of drones for commercial enterprise and in everyday life. The agency's dynamic science portfolio under Bridenstine includes a life-seeking Mars rover scheduled to launch in July 2020, enhancing the nation's fleet of Earth-observing satellites and final preparations of the James Webb Space Telescope.

Prior to serving at NASA, Bridenstine was elected in 2012 to represent Oklahoma's First Congressional District in the U.S. House of Representatives, where he served on the Armed Services Committee and the Science, Space and Technology Committee.

Bridenstine's career in federal service began in 1998 as a pilot in the U.S. Navy, flying the E-2C Hawkeye off the USS Abraham Lincoln aircraft carrier. It was there that he flew combat missions in Iraq and Afghanistan and accrued most of his 1,900 flight hours and 333 arrested landings on an aircraft carrier. He later moved to the F-18 Hornet and flew at the Naval Strike and Air Warfare Center, the parent command to TOPGUN.

After transitioning from active duty to the U.S. Navy Reserve, Bridenstine returned to Tulsa, Oklahoma, to be the executive director of the Tulsa Air and Space Museum & Planetarium.

Bridenstine completed a triple major at Rice University and earned his MBA at Cornell University. He and his wife, Michelle, have three children.

Speakers

James Reuter

NASA Associate Administrator

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.

Niki Werkheiser

Lead, Lunar Surface Innovation Initiative
NASA Space Technology Mission Directorate

Niki Werkheiser is the NASA Headquarters Executive for the Game Changing Development (GCD) Program within the Space Technology Mission Directorate (STMD). GCD advances technologies for future space missions. Concurrently, she serves as the Lead for the Agency's Lunar Surface Innovation Initiative (LSII), with the objective of spurring the creation of novel technologies needed for lunar surface exploration. Prior to her current roles, Ms. Werkheiser led the Agency's In-Space Manufacturing (ISM) efforts, including the development and implementation of on-demand manufacturing and repair capabilities. She brings a wealth of expertise and a proven approach to managing complex programs. Ms. Werkheiser is particularly passionate about creating competitive programs and public-private partnerships across government, industry, academia, and non-profit organizations. Ms. Werkheiser earned a M.S. from the University of Alabama in Huntsville with an emphasis in Gravitational and Space Biology, as well as a B.S. in Biology and a B.A. in Russian Studies.

Speakers

Ben Bussey

Lunar Surface Innovation Initiative Lead,
Johns Hopkins Applied Physics Laboratory

Dr. Bussey is a planetary scientist who is currently the lead of the APL team supporting NASA's Space Tech's Lunar Surface Innovation Initiative. He earned a BA in Physics from Oxford University and a Ph.D. in Planetary Geology at University College London before moving to the United States. He gained both science and mission experience while working at the Lunar and Planetary Institute in Houston, the European Space Agency, Northwestern University and the University of Hawaii, before joining the Johns Hopkins University Applied Physics Laboratory.

Bussey's research concentrates on the remote sensing of the surfaces of planets, particularly the Moon. He has a specific interest in the lunar poles, producing the first quantitative illumination maps of the polar regions. He co-authored the Clementine Atlas of the Moon, the first atlas to map both the lunar near side and far side in a systematic manner.

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

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

Rachel Klima

Lunar Surface Innovation Consortium Director,
Johns Hopkins Applied Physics Laboratory

Dr. Rachel Klima is the Director of the Lunar Surface Innovation Consortium and a senior 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 currently serves as the Deputy PI of the Lunar Trailblazer Mission and also Deputy PI of the VORTICES SSERVI node.

Speakers

Christopher Baker

Small Spacecraft Technology and Flight Opportunities
Program Executive, NASA

Christopher Baker currently serves as the program executive for NASA's Space Technology Mission Directorate Small Spacecraft Technology program, which seeks to expand the ability to execute unique missions through the rapid development and demonstration of capabilities for small spacecraft applicable to exploration, science and the commercial space sector. Baker also serves as the program executive for NASA's Flight Opportunities program that facilitates rapid demonstration of promising technologies for space exploration, discovery, and the expansion of space commerce through suborbital testing with industry flight providers. Baker previously held various positions in atmospheric and suborbital flight testing at the Armstrong Flight Research Center, and managed an agency wide early stage research and development program from NASA Headquarters. Baker is a graduate of the Worcester Polytechnic Institute where he received a Bachelor of Science in Aerospace Engineering and a Master of Science in Mechanical Engineering.

Anthony Calomino

Portfolio Manager,
NASA STMD Space Nuclear Technologies

Dr. Anthony M. Calomino is the portfolio manager for NASA STMD Space Nuclear Technologies. Dr. Calomino's previous roles included the Chief Engineer and Deputy Program Manager for the NASA Game Changing Development Program. He has been with NASA since 1985 serving as a high temperature materials and structures engineer working in areas related to air-breathing propulsion, hypersonic airframes, thermal protection systems, and nuclear thermal propulsion. He has a bachelor's and master's degree in Structures and Engineering Mechanics, and obtained a doctorate in Materials Science from Northwestern University. His primary technical background is in durability and damage modeling for high temperature materials and composites towards hypersonic applications.

Jason Derleth

Program Executive,
NASA Innovative Advanced Concepts (NIAC) Program

Mr. Jason Derleth is an aerospace engineer and technology analyst with experience at NASA Headquarters, the Jet Propulsion Lab, and private industry. He is also an author and craftsman. Jason graduated from St. John's College with a BA in Philosophy in 2000, where he won the Baird Prize for Excellence in the Arts or Sciences for a hand-built cello. He followed this SM in Aero Astro engineering from MIT in 2003. He began working at the Jet Propulsion Laboratory a month after graduation. In 2005, he was awarded the NASA Exceptional Public Service Medal for his work in the Exploration Systems Architecture Study. He transferred to the NASA Civil Service in 2008, joined NIAC as Program Manager in 2011, and became Program Executive in 2015.

Speakers

Lindy Elkins-Tanton

Managing Director, Interplanetary Initiative
Arizona State University

Lindy Elkins-Tanton is the Principal Investigator of the NASA Psyche mission, Managing Director of the Interplanetary Initiative at Arizona State University, and co-founder of Beagle Learning, a tech company training and measuring collaborative problem-solving and critical thinking. Her research and efforts are focused on a positive human space exploration future, the effective leadership of teams, and education for the future of society. She has led four field expeditions in Siberia. She served on the Planetary Decadal Survey Mars panel, and the Mars 2020 Rover Science Definition Team, and now serves on the Europa Clipper Standing Review Board. In 2010 she was awarded the Explorers Club Lowell Thomas prize. Asteroid (8252) Elkins-Tanton is named for her. In 2013 she was named the Astor Fellow at Oxford University. She is a fellow of the American Geophysical Union, and of the American Mineralogical Society, and in 2018 she was elected to the American Academy of Arts & Sciences. In January 2020, she was awarded The Arthur L. Day Prize and Lectureship, by the National Academy of Sciences, for her lasting contributions to the study of the physics of Earth, and for illuminating the early evolution of rocky planets and planetesimals. Elkins-Tanton received her B.S., M.S., and Ph.D. from MIT. Together we are working toward a positive space exploration future, and toward creating a generation of problem-solvers.

Wes Fuhrman

Lunar Surface Innovation Consortium Surface Power Facilitator,
Johns Hopkins Applied Physics Laboratory

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

Speakers

Michael Goryll

Professor, School of Electrical, Computer,
and Energy Engineering at Arizona State University

Dr. Michael Goryll is a Professor at the School of Electrical, Computer and Energy Engineering at Arizona State University. He received his Diplom (1997) and PhD (2000) degrees in physics from the RWTH Aachen University, Germany. He has held a research position at the Institute of Bio- and Nanosystems at the Research Center Jülich, Germany from 1996 to 2007, where he worked on Ge and SiGe nanostructure growth and the development of a strain relaxed buffer process for strained Silicon-On-Insulator (sSOI) substrates using Chemical Vapor Deposition. Besides his efforts in Materials Science he became involved in the process development for a vertical nano-MOSFET and a field-effect transistor for whole-cell-based sensing. He held a post-doc position at Arizona State University, USA from 2003 to 2005, where he started his research on ion channel sensors. He joined Arizona State University as a faculty member in 2007 and established a research program on solid-state nanopore devices for protein analysis, featuring low-noise wide-bandwidth electronics for ion current recording. He has also been involved in projects featuring flexible ion-sensitive field effect transistor devices as well as impedimetric hydrogel-based sensors for bio- and environmental sensing. Based on his expertise in optical and electrical characterization techniques, he has been involved in projects using admittance spectroscopy to studying defects in wide-bandgap semiconductors and Perovskite Solar Cells. Dr. Goryll's current research interests cover manufacturing process development of Interdigitated Back Contact photovoltaic cells as well as process optimization and reliability studies on thin, bendable, light-weight silicon solar cells. Dr. Goryll has served as the Undergraduate Program Chair in Electrical, Computer and Energy Engineering at Arizona State University from 2013 until 2016, where he helped launch the ABET-accredited online-delivered BS program in Electrical Engineering. Dr. Goryll is a recipient of the NSF CAREER award in 2012 as well as the 2012 Fulton Schools of Engineering Best Teacher Award.

Jenn Gustetic

Program Executive,
Small Business Innovation Research (SBIR/STTR)

Ms. Gustetic is an experienced innovation leader in the federal government and a policy entrepreneur, having served as the Program Executive for Small Business Innovation Research (SBIR/STTR) at NASA Headquarters (2016-present), the Assistant Director for Open Innovation at the White House Office of Science and Technology Policy (2014-2016), the program executive for prizes and challenges at NASA (2012-2014), co-chair of the Partnership for Public Service's Innovation Council (2018-today), co-chair of the National Science and Technology Council (NSTC) Interagency Maker working group (2016-2018), research fellow at the Harvard Kennedy School (2017-2019), and board of trustees member of the Van Alen Institute (2016-today). In her current role, Ms. Gustetic funds small businesses approximately $200M annually for research, development, and demonstration of innovative technologies that fulfill NASA needs and have significant potential for successful commercialization.

Ms. Gustetic holds a bachelors degree in aerospace engineering from the University of Florida and a master's degree in technology policy from the Massachusetts Institute of Technology. She has published numerous writings on innovation including in the MIT Press, Space Policy Journal, New Space Journal, and Issues in Science and Technology.

Speakers

Marija Ilic

Senior Research Scientist,
Massachusetts Institute of Technology

Marija Ilic is a Professor Emerita at Carnegie Mellon University (CMU). She currently holds two positions at the Massachusetts Institute of Technology (MIT): Senior Staff in the Energy Systems Group 73 at the MIT Lincoln Laboratory, and Senior Research Scientist at the MIT Laboratory for Information and Decision Systems (LIDS). She is an IEEE Life Fellow. She was the first recipient of the NSF Presidential Young Investigator Award for Power Systems signed by late President Ronald Reagan. She has co-authored several books on the subject of large-scale electric power systems, and has co-organized an annual multidisciplinary Electricity Industry conference series at Carnegie Mellon (http://www.ece.cmu.edu/~electriconf) with participants from academia, government, and industry. She was the founder and co-director of the Electric Energy Systems Group (EESG) at Carnegie Mellon University (http://www.eesg.ece.cmu.edu). Currently she is building EESG@MIT, in the same spirit as EESG@CMU.

Amy Kaminski

Program Executive for Prizes and Challenges,
NASA

Dr. Amy Kaminski currently serves as program executive for prizes and challenges at NASA Headquarters in Washington, DC, where she works to develop strategies to expand the space agency's use of a variety of open innovation methods in its research and exploration activities. She served previously as senior policy advisor in the Office of the Chief Scientist, where she led an initiative to support and expand NASA's involvement of citizens as contributors to the agency's research activities. Before joining NASA, Kaminski served as a program examiner at the White House Office of Management and Budget (OMB). She also has held positions in the Federal Aviation Administration and the National Space Society. Kaminski earned a Ph.D. in science and technology studies from Virginia Tech, an M.A. in science, technology, and public policy from The George Washington University and a B.A. from Cornell University in earth and planetary sciences.

Speakers

Isik Kizilyalli

Associate Director for Technology,
Advanced Research Projects Agency – Energy (ARPA-E)

Dr. Isik C. Kizilyalli currently serves as the Associate Director for Technology at the Advanced Research Projects Agency – Energy (ARPA-E). In this role, Dr. Kizilyalli supports the Deputy Director for Technology in oversight of all technology issues relating to ARPA-E's programs as well as assisting with program development, Program Director and Fellow recruitment, and coordinating project management across the Agency. Kizilyalli's focus at ARPA-E includes power electronics, wide bandgap semiconductors, electronic systems for hostile environments, electrification of transport (aviation, ships, automotive), subsurface instrumentation, novel drilling concepts, medium voltage DC distribution grids, and grid resiliency against EMP and space weather threats. He was elected a Fellow of the Institute of Electrical and Electronics Engineers (IEEE) in 2007 for his contributions to Integrated Circuit Technology. He also received the Bell Laboratories' Distinguished Member of Technical Staff award and the Best Paper Award at the International Symposium on Power Semiconductors and Integrated Circuits in 2013. Dr. Kizilyalli holds his B.S. in Electrical Engineering, M.S. in Metallurgy, and Ph.D. in Electrical Engineering from the University of Illinois Urbana-Champaign. He has published more than 100 papers and holds 120 issued U.S. patents.

Daniel Lockney

Technology Transfer Program Executive,
NASA

Daniel Lockney is the Technology Transfer Program Executive at NASA Headquarters in Washington, DC, responsible for Agency-level management of NASA intellectual property and the transfer of NASA technology to promote the commercialization and public availability of Federally-owned inventions to benefit the national economy and the U.S. public. Lockney oversees policy, strategy, resources, and direction for the Agency's technology commercialization efforts. NASA has had a long history of finding new, innovative uses for its space and aeronautics technologies, and Lockney is the Agency's leading authority on these technologies and their practical, terrestrial applications. Lockney studied American Literature at the University of Maryland, Baltimore County and creative writing at Johns Hopkins University. He started his NASA career as a contractor in 2004, converting to civil service in 2010. He lives in University Park, Maryland, with his wife and two space pups, Astro and Cosmo.

Speakers

Mark McDonald

Chief Architect,
NASA Space Tech

Mark McDonald was named Chief Architect for the Space Technology Mission Directorate (STMD) at NASA Headquarters in August 2019. In this role, he provides executive leadership in establishing a long term vision for STMD investments, with an annual investment value of $1.1 billion. McDonald was the international formulation team lead for the Gateway Lunar Architecture from 2012 through 2018. Previously, McDonald served in many managerial roles at Johnson Space Center including Deputy Manager of the Design Integration Office in the Constellation program, the Branch Chief of the Avionics Systems Division's Product Development Branch, the deputy manager of Avionics Project Management Office, and Chairman of the International Space Station Architecture Integration Team. McDonald began his NASA career in 1987 as an electrical engineer at Jet Propulsion Laboratory and transferred to Johnson Space Center in 1990. McDonald has a bachelor's degree in electrical engineering from the Texas A&M University and a Master's Degree in Aerospace Engineering from the University of Southern California. He has received numerous NASA awards and honors including a 2013 NASA Exceptional Achievement Medal, a 2004 Silver Snoopy Award and 2000 & 2001 Space Flight Awareness Awards.

Mason Peck

Chief Technologist of the Space Exploration Sector,
Johns Hopkins Applied Physics Laboratory

Mason Peck is the Chief Technologist of the Space Exploration Sector at the Johns Hopkins Applied Physics Laboratory. Prior to coming to APL, Peck was most recently a professor in the Sibley School of Mechanical Engineering at Cornell University, where, except for the time he spent as NASA's chief technologist from late 2011 until early 2014, he has worked since 2004. Before joining Cornell he worked on space systems at several companies, both in civil and national security areas. Peck also advises a number of public and private organizations and is well known in the space community for his depth and breadth of knowledge, and the pathfinding technologies he and his students developed. Peck has a Bachelor of Science in aerospace engineering and a Bachelor of Arts in English from the University of Texas, a Master of Arts in English language and literature from the University of Chicago, and a Master of Sciences and a Doctor of Philosophy in aerospace engineering from the University of California, Los Angeles.

Speakers

Jan Rogers

Technical Integration Lead,
STMD Space Technology Research Grants Program

Jan Rogers has extensive experience in materials science and characterization and Program/Project management. She is the Technical Integration Lead for STMD's Space Technology Research Grants Program and has supported strategic integration efforts in STMD. She has served as the Technical Lead for the HEO, Space Life and Physical Sciences' Materials Science and Biophysics Portfolio at MSFC. She served as Acting Chief for the MSFC Space Environmental Effects Branch. Jan has served as the lead scientist or Co-Investigator on numerous funded proposals. Research efforts include microgravity and materials science studies. Her technology development efforts include development of instrumentation and methods to study alloys and metals as well as properties of materials at high temperatures. Jan Rogers earned a Ph.D. in Chemical Engineering from the University of Colorado, Boulder and was supported by NASA's Graduate Student Researchers Program.

Michael Ryschkewitsch

Sector Head for the Space Exploration Sector,
Johns Hopkins University Applied Physics Laboratory

Dr. Michael G. Ryschkewitsch is the Sector Head for the Space Exploration Sector of the Johns Hopkins University Applied Physics Laboratory overseeing APL's portfolio of space programs for both NASA and national security sponsors. He leads an experienced science, engineering and program management cadre to pursue groundbreaking space opportunities abd who are making critical contributions to a wide variety of nationally and globally significant technical and scientific challenges. Before joining the APL, he served for over thirty years at NASA with the last seven years as the NASA Chief Engineer.

Chuck Taylor

Project Manager,
Vertical Solar Array Technology (VSAT)

Mr. Taylor is a Project Manager at NASA Langley Research Center. He has led multiple projects related to both autonomous in-space assembly and solar power generation while at the Center. Prior to coming to the LaRC, he was the NASA Space Technology Mission Directorate Principal Investigator/Technologist for the Space Power and Energy Storage portfolio. In this capacity, he initiated multiple large-scale efforts to advance technologies associated with photovoltaics, Li Battery technologies, and Hydrogen Fuel Cells. Prior to joining NASA Mr. Taylor was a Project Manager at the Defense Advanced Research Projects Agency where he focused on tracking and engaging moving ground targets by combining advanced radar signal processing techniques with direct communications to weapons in flight. Other significant research activities include, unmanned systems design and analysis for the Navy in the early 1990's. During this period, Mr. Taylor was an original member of the Predator UAV design team.

Table of Contents for Abstracts

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Solar-Powered Additive Manufacturing on the Moon. S. D. Anderson[1] and J. Thangavelautham[2], [1]Space and Terrestrial Robotic Exploration (SpaceTREx) Laboratory, University of Arizona, 1130 N. Mountain Ave, Tucson, AZ 85721. (Contact: sanderson@email.arizona.edu)

Abstract: As humans prepare to take steps deeper into the solar system, a specialized set of space infrastructure in strategic locations will be necessary to support long duration robotic and human missions. To be successful, we will need to construct communication relays, robotic and human habitats, repair stations, radiation shelters, road networks, and many other structures. With reduction of fuel costs at a premium for efficient mission design and sustainability, importing the required material from Earth to build these structures is too expensive. We need innovative advancement in material extraction and construction methods that make use of in-situ resources.

A multitude of additive manufacturing techniques have risen to the forefront of construction methods for their ability to be sent in advance of the primary mission and for critical infra-structures to be built autonomously. There remain two distinct challenges inherent in this concept: the operation needs to be supplied material and it must have a sufficient energy source to process the material into its final form.

In an effort to confront these challenges, we are working to develop an additive manufacturing process based on the principles of the Selective Laser Sintering (SLS) technique, whereby a heat source (typically a CO2 laser) heats the material to just below its liquefaction point before returning it to a solid form. By replacing the laser in the SLS process with a large Fresnel lens, we aim to focus enough sunlight to be able to sinter in-situ material and create solid shapes. In this way, the system fully relies on renewable solar energy for its operation.

NASA's Artemis mission is intended to be a proving ground for new technologies that will be necessary for future deep-space endeavors by first establishing those technologies on the Moon. It turns out that the Moon also provides an ideal testbed for solar sinter technology. With a high solar irradiance and a fine particulate top surface, sinter operations would be able to print directly onto the surface with a powerful beam.

In this presentation, we propose the development of solar sinter devices that will be capable of sintering lunar regolith and other materials. We will detail the conceptualization, design, and experimental prototype of a working solar-powered additive manufacturing machine.

References:

[1] Meurisse A. et al. (2018) *Solar 3D printing of lunar regolith,* Acta Astronautica, 152. [2] Imhof, B. et al. (2017) *Advancing Solar Sintering for Building a Base on the Moon,* 68th International Astronautical Congress. [3] Kayser, M. (2011) *The Solar Sinter,* https://www.dezeen.com/2011/06/28/the-solar-sinter-by-markus-kayser/, Accessed December 2019. [4] Synder M. et al. (2013) AIAA Space 2013 Conference and Exposition, AIAA 2013-5439. [5] Cesaretti, G. et al. (2014) *Building Components for an Outpost on the Lunar Soil by Means of a Novel 3D Printing Technology,* Acta Astronautica, 93, 430-450.

Stored Mechanical Energy and Carbon Onion Resilience Under Space Radiation. V.M Ayres[1], K. Xie[1], H. C. Shaw[2], A.Hirata[3], [1] Michigan State University, East Lansing, MI, 48824, USA, [2]NASA Goddard Space Flight Center, Greenbelt, MD, 20771, USA, [3] Tokyo Institute of Technology, Tokyo, Japan. (Contact: ayresv@msu.edu)

Introduction: Nano-carbons are a promising approach to lubrication challenges in space including vacuum, radiation and non-terrestrial temperature regimes. Planar graphite, while an excellent lubricant on earth, undergoes structural collapse in vacuum and knock-on collision generated amorphitization in response to heavy ions in the solar wind. Carbon onions have shown robust performance in vacuum environments [1] and are under investigation by our group and others for their space radiation and temperature resilience [2].

Results: The responses of carbon onions with increasing polygonal character due to increasing temperature growth conditions were investigated under heavy ion irradiation at the Facility for Rare Isotope Beams (FRIB) at Michigan State University [3]. Primary beams of fully stripped Calcium-48, and Argon-40 with 140 or 70 MeV per nucleon kinetic energies were used to generate realistic space conditions. Stored elastic energy and layer number were investigated using analysis of pre- and post- irradiation high-resolution transmission electron microscope (HRTEM) images. As the radiation dose increased, carbon onion mechanical energy storage counterintuitively increased due to a decrease in disorder, reproducing sp2/sp3 layer characteristics of carbon onions grown at a higher temperatures. A stored energy range that correlates with a further radiation-induced conversion to planar graphite was identified (Fig. 1). Observations may be explained by different allowed responses to radiation-induced defects in radial (carbon onion) versus planar (graphite) graphene layers.

Conclusions. The results indicate that for space lubrication applications, lower temperature synthesis carbon onions, initially less polygonal and more defective, may be more resilient to heavy ion radiation.

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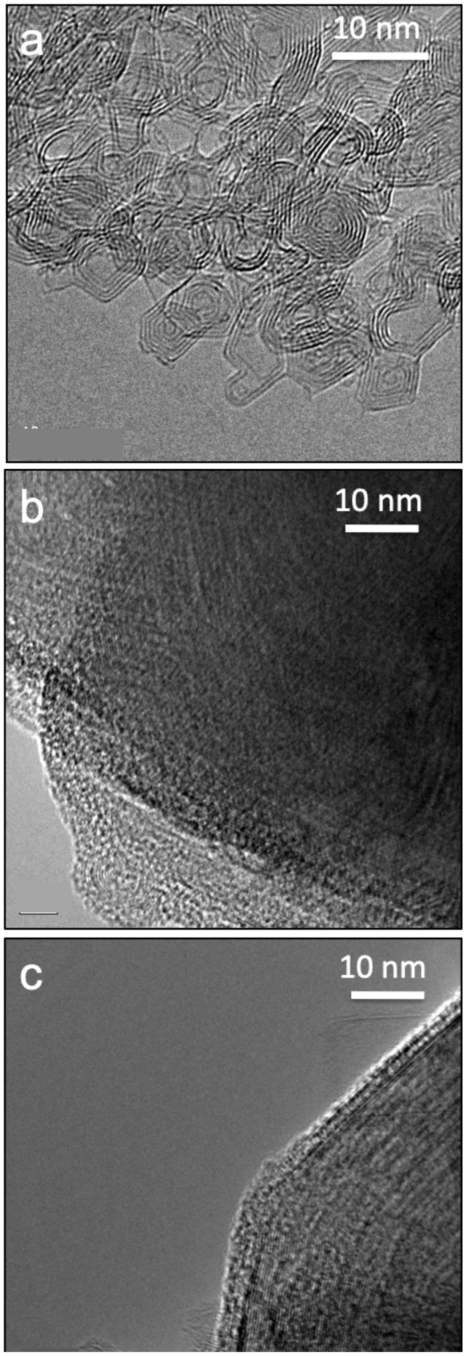

Figure 1. Conversion of (a) highly polygonal minimum-defect carbon onions into (b) amorphous and (c) planar graphite under heavy ion irradiation through release of elastic energy.

ISRU Value Chain Bertrand Barette, Air Liquide Advanced Technologies US LLC, Houston, TX 77024, Bertrand.baratte@airliquide.com

Introduction: Surface Power and ISRU are complementary components of a sustainable Lunar Infrastructure. Many of the technologies needed to realize this infrastructure are either existant on Earth or are in development. The author has developed a roadmap identifying where these technologies are located, their state of maturity and two approaches to qualifying them for the moon.

Granular Morphology Metrics of JSC-1A Lunar Regolith Simulant. J. W. Bullard[1] and E. J. Garboczi[2], [1]Texas A&M University, 3136 TAMU, College Station, Texas, [2]National Institute of Standards and Technology, 325 Broadway, Boulder Colorado. (Contact: jwbullard@tamu.edu)

Introduction: The size and shape distribution of Lunar soil and dust particles will have a significant impact on future construction and dust mitigation efforts on the Moon. Additive manufacturing by sintering depends on the packing and curvature gradients within powder compacts [1,2]. Extrusion and flowability of particle suspensions depends sensitively on particle shape [3-5]. And electrostatic methods to control dust will be impacted by the way that the dielectric polarizability depends on particle shape [6]. This paper uses a combination of X-ray microtomography and spherical harmonic analysis to mathematically characterize the shape of JSC-1A Lunar regolith simulant particles [7].

Methods: JSC-1A powder is fixed with epoxy in a cylindrical tube and scanned by X-ray microtomography with a minimum voxel size of 0.5 μm. The individual radiograph slices are stacked and the intensity thresholded to isolate over 130,000 individual particles, which are then numerically extracted for individual analysis. The 3D shape is represented as a truncated spherical harmonic (SH) expansion up to a degree of at least 15, thereby creating a closed-form, continuous analytical model of the surface. Multiple properties of the shape and size of each particle can be computed from this model.

Results: The population of JSC-1A particles were characterized in terms of their volumes, surface areas, lengths, widths, thicknesses, integrated mean curvature, moment of inertia tensor, and degree of convexity. The measurements will be presented as statistical distributions. In addition, a random parking algorithm is used to generate virtual Lunar soils of different compaction densities, from which the pore size distribution is readily computed.

Conclusions: The use of X-ray μCT and spherical harmonic analysis enables high-fidelity calculations of Lunar regolith shape and size properties, in addition to virtual 3D packings of Lunar soils. Future work will include calculations of dielectric polarizability, intrinsic viscosity, and geotechnical properties of soils such as friction angle and cohesion for real and simulated Lunar material. Furthermore, the virtual packings can be used in the future as traceable digital twins for subsequent testing and validation of models for dust mitigation and additive manufacturing on the Moon.

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Advanced Power Electronics with Impedance-Based Stability-Enhanced Controls

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Introduction: The Center for Power Electronics Systems (CPES) at Virginia Tech has been involved with aerospace technology since its inception in the early 1970s, when it developed models of switching power converters in collaboration with the NASA Goddard Space Flight Center, and later on with the NASA Lewis Research Center developing impedance-based stabilty criteria for the International Space Station, among other programs. These methods proved crucial in the early 2000s when CPES participated actively in the development of ac stability criteria for more electric aircraft, working closely with Boeing and its numerous partners in the 787 electrical system.

More recently, CPES has contributed to the dynamic analysis and interactions created by power electronics in grid applications, given the large-number of power electronics that continue to be deployed at an ever increasing rate. This has allowed CPES to unveil a rich set of dynamic interactions between grid-tied inverters integrating renewable energy into the grid—among other applications, which for instance can make photovoltaic inverters appear as constant power loads from a small-signal standpoint; triggering interactions and oscillations threatening the operation of the grid. Further, CPES has shown the benefits in terms of active power generation when grid-tied inverters operate with grid-forming rather than grid-following controls, demonstrating how the generation capacity can be effectively doubled in specific cases.

The above theoretical findings allowed CPES to finally develop, in collaboration with Boeing for low-voltage systems, and later on with the Office of Naval Research (ONR) for medium-voltage systems, power-electronics based impedance measurement units (IMU) capable of perturbing (small-signal) ac and dc distribution systems to measure the impedances seen at given interfaces. These are needed to monitor and assess the stability conditions present in the system, being to date the only research center with a three-phase measurement capability.

This technology has been extended to operate in modular Silicon-Carbide (SiC) based IMUs developed for Newport News Shipbuilding (NNS), taking advantage of the power processing characteristics of this wide-bandgap power semiconductors. The IMU has played a key role aiding in the development of new advanced staibility theory at CPES for the assessment of stability in single-phase and three-phase unbalanced networks. Based on it, over the past year CPES has been studying the impact of prime movers in aircraft electrical systems together with NASA Glenn Research Center, and in data centers through an ongoing collaboration with Google. It has developed too an impedance measurement capacity integrated with the control system of ac and dc power converters enabling them to monitor continuously the stability conditions in electrical power systems.

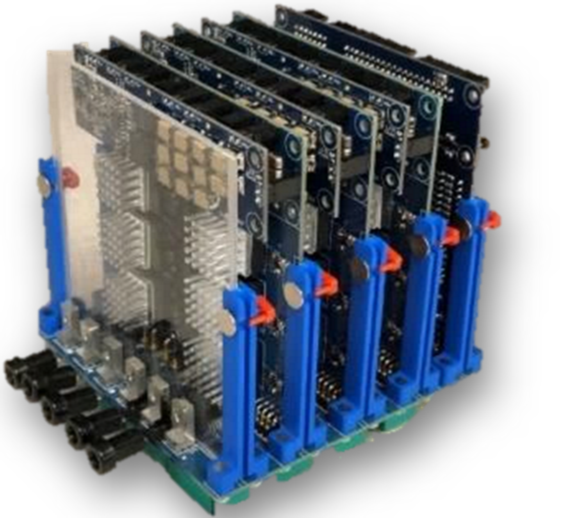

Figure 1 Three-phase matrix converter recently developed at CPES (SiC MOSFETs, 20 kW, 480 V ac, 12 kW/l)

CPES has additionally a long history developing high power density SiC-based power electronics for aircraft power systems, having developed new circuit topologies and control methods to achieve efficiency levels > 99 %, and power density figures > 10 kW/l in numerous single- and three-phase rectifiers and inverters; from hundreds of watts to hundreds of kilowatts, seeking to minimize too the size and weight of electromagnetic interference (EMI) filters through innovative power conversion and control solutions in collaboration with Boeing, THALES, Collins Aerospace, SAFRAN, Raytheon Technologies, Lockheed Martin, GE Aviation, Airbus, and VPT, among others.

This presentation will to summarize the most recent and relevant contributions that CPES has had in aerospace power applications aiming at future lunar surface power operations.

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Lunar Autonomous Scalable Emitter and Receiver (LASER) System, NASA 2020 BIG Idea Challenge.

Centers, R., Kezer, L., Schertz, J., Purrington, C., Broslav, T., Janikowski, A., Hauser, A., Diaz-Flores, A., Moreno, J., Kalita H., Vance, L., Thanga, J., Sowers, G., Colorado School of Mines, Golden, CO 80401 USA. (Contact: centers@mymail.mines.edu)

Introduction: Lunar PSR exploration is constrained by lack of power. With no endogenous sunlight, non-nuclear rover batteries will run out unless recharged. Laser power transmission from sunlit sites to rovers operating in PSRs can allow extended operations, both in distance and duration.

Laser based power transmission represents an enabling technology for moving power from energy rich regions to areas of high demand, while being able to overcome the dramatic topography of the lunar poles [1-4]. To provide the earliest opportunity for flight demonstration of this critical technology, we design and demonstrate a low power, minimal mass laser power beaming system that can be mounted as an ancillary payload on an early CLPS lander.

Architecture: Consisting of a laser, beam director, target identification system, and multiple FemtoSat receivers [5], this integrated system is able to test key objectives incrementally. We test methods of ejecting and locating the receiver on the lunar surface, and develop a pointing system to aim the laser at the receiver. Power transfer is tested under simulated lunar conditions in a cryogenic vacuum chamber filled with regolith simulant.

Application: We are developing use cases to support science goals. On an ancillary payload mission, our system will allow other technology demonstrations or other scientific missions to do more or go further. Given a view into a PSR, the transmitter can support remote analysis of volatiles by heating cryogenic regolith. Detailed prospecting could occur over hundreds of square meters, informing impact gardening models without requiring physical access to PSRs. Similarly, potential subsurface volatiles could be exposed by heating sunlit regolith with the laser. With the ability to heat things at a distance and power other missions, the LASER system provides a “menu” of options to be paired with on ancillary payloads.

Outcome: By reducing risk, demonstrating feasibility, and increasing the technology readiness level (TRL) of this power beaming concept, this project has the potential to lead to the deployment of power beaming technoloiges for exploring PSRs.

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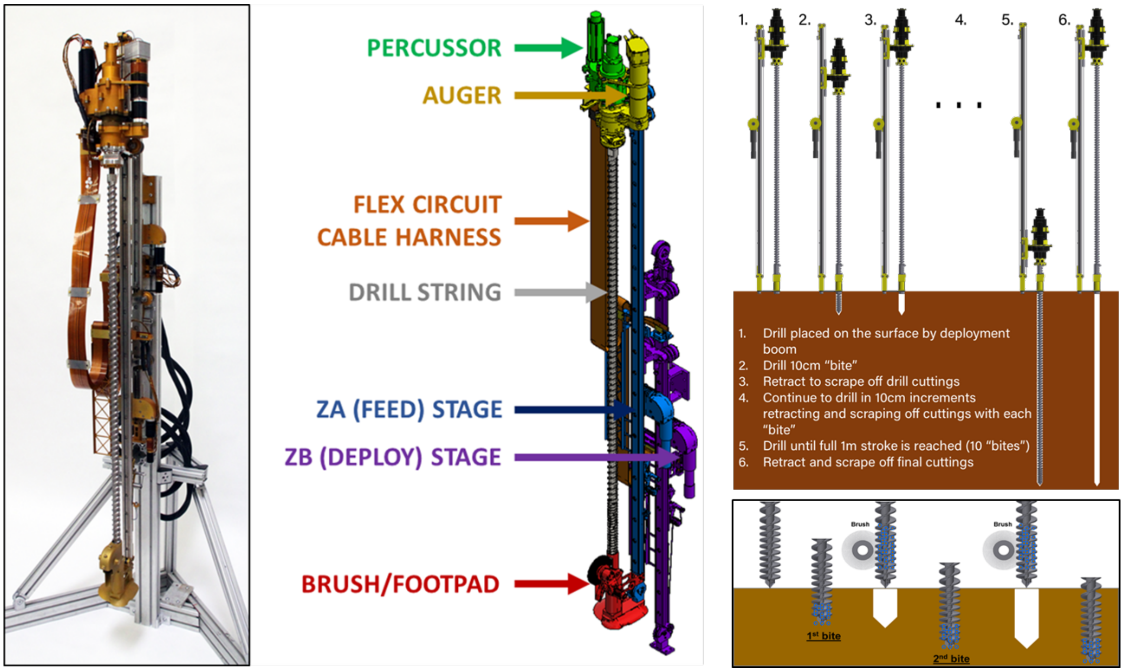
[5] J. Thangavelautham et al., Interplanetary CubeSat Workshop 6 (2016)

TRIDENT: The Regolith and Ice Drill for Exploring New Terrain. P. Chu[1], K. Zacny[1], V. Vendiola[1], J. Quinn[2], J. Kleinhenz[3], [1]Honeybee Robotics, 2408 Lincoln Blvd., Altadena, CA 91001, [2]NASA Kenedy Space Center, Houston, TX, [3]NASA Johnson Space Center, Houston, TX. (zacny@honeybeerobotics.com)



1. Drill placed on the surface by deployment boom
2. Drill 10cm "bite"
3. Retract to scrape off drill cuttings
4. Continue to drill in 10cm increments retracting and scraping off cuttings with each "bite"
5. Drill until full 1m stroke is reached (10 "bites")
6. Retract and scrape off final cuttings

Figure 1. TRIDENT Rotary-Percussive Drill System.

Introduction: For over two decades, Honeybee Robotics has been developing 1 m class sample acquisition drills for acquisition of volatile rich samples from planetary surfaces. TRIDENT, the latest drill system, is at TRL6 and has been designed and fabricated specifically for the lunar missions. However, the drill and sample delivery system can be infused into any other mission requiring samples from up to 10 m depth (with an addition of a carousel).

The primary components of the drill consist of 1. Rotary-Percussive Drill Head, 2. Sampling Auger, 3. Brushing Station, 4. Feed Stage, and 5. Deployment Stage. The TRIDENT drill auger includes an integrated temperature sensor to provide subsurface temperatures while drilling. Drill telemetry will additionally be used to determine regolith strength, and in combination with other instruments, the fractional content and state of ice present. Additionally, a bit integrated heater will provide capabilities for additional measurements including thermal conductivity of the lunar soil.

To reduce sample handling complexity, the drill auger is designed to capture cuttings as opposed to cores. High sampling efficiency is possible through a dual design of the auger. The lower section has deep and low pitch flutes for retaining of cuttings. The upper section has been designed to efficiently move the cuttings out of the hole. The drill uses a "bite" sampling approach where samples are captured in ~10 cm depth intervals all the way to 1 m depth. This allows for stratigraphy to be maintained while reducing drilling power and forces.

The Engineering Test Unit (ETU) of TRIDENT has been tested in NASA GRC's lunar vacuum chamber at ~10^-5 torr vacuum and ~150 K temperature. The ETU has also been successfully vibration tested at NASA KSC.

CLPS Missions: TRIDENT will fly on PRIME-1 and VIPER CLPS missions. For PRIME-1, TRIDENT will fly on a CLPS lander alongside the Mass Spectrometer observing lunar operations (MSolo) instrument. TRIDENT will make a pile of cuttings and MSolo will detect volatiles sublimating from the cuttings pile. VIPER will have TRIDENT mounted to a polar lunar prospecting rover with Near InfraRed Volatiles Spectrometer Subsystem (NIRVSS), MSolo and NSS. NIRVSS and MSolo will detect volatiles from the cuttings pile generated by the drill.

The TRIDENT drill passed PDR and is scheduled to have CDR in the summer of 2020.

Scalable Wireless Charging System for Lunar Rovers C. Corpa De La Fuente, Astrobotic Technology, 1016 North Lincoln Avenue, Pittsburgh, PA 15233 (cedric.corpadelafuente@astrobotic.com)

Introduction: Generating, storing, and transmitting power is a critical infrastructure need for all human and robotic activities. Traditional space systems operate through nuclear, solar, or tethered power mechanisms that require great complexity and process to qualify and operate. Tethered systems are hindered tremendously by mechanically mated components that are prone to regolith incursion. Regolith clinging is a significant risk for mobile assets such as lunar rovers that must either restrict the surface operation speed or employ expensive counter-measures to control the clinging effects of the abrasive lunar regolith. An alternative solution to mitigate these risks is to transfer power and data wirelessly. Trends in the miniaturization of electronics and increasing efficiency of switching components, enable proximity charging to be a viable option for space applications. Systems such as WiBotic's wireless charging platform would weigh 1 kg and consist of a base station(0.98 kg) and power receiver (.04 kg)that can be configured in many orientations (Figure 1) to transmit at least 100W of power. Astrobotic is partnered with WiBotic to develop this system for space applications.

Fast and Scalable Charging Applications: There are several applications that necessitate proximity chargers in space. In relation to the Moon, these include supporting marsupial roving missions, enabling robotic systems that do not contain onboard nuclear or solar power generators, charging toolkits on crewed lunar terrain vehicles (LTVs), and powering the heaters of critical devices to survive the lunar night. Marsupial missions have been proposed in the past with large rovers and scouts that deploy from them (such as Astrobotic's 300 kg Polaris rover and 3.5 kg CubeRover) to explore the lunar surface. These scouts could be used for resource prospecting and hazard avoidance for larger, expensive assets. If a proximity charger were mounted to the base of a larger rover then scouts could be recharged by the larger rover directly through its onboard power source. Similarly, proximity chargers could simplify the designs of large rovers by removing the need to contain onboard power systems and instead receiving power from a proximity charger affixed to a lander or deployable solar array. Larger implementation of proximity charging could transfer multi-kilowatt power to these systems.

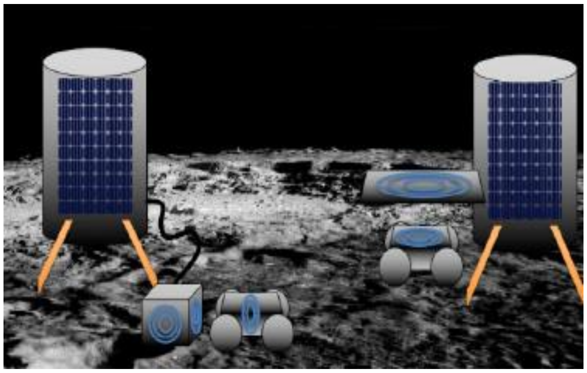


Figure 1: Wireless charging concepts from lander to small rovers such as CubeRovers.

Technology Advanced Through Investment: The Commercial Lunar Payload Services (CLPS) program plays a pivotal role in enabling these precursor missions. NASA has funded Astrobotic and WiBotic to co-develop a high power density wireless charging solution through the SBIR.

Specifications: The resulting system will have the following features:

- Dust tolerant design for 1 µm lunar regolith particles
- Charging range of 0-4cm (horizontal spacing), +/-5cm (lateral misalignment), 0-70deg (angular misalignment)
- Operational temperature range of -200C to +86C to enable operations at the lunar pole and equator

Figure 2 Rovers such as Astrobotic's Polaris rover could increase its mission capabilities by supplementing or replacing solar charging with a fast, lightweight proximity charging system.

A MILLIWATT RADIOISOTOPE THERMOELECTRIC GENERATOR FOR LUNAR EXPLORATION.

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Introduction: The ability to support and implement novel space missions that will explore and operate in extreme, inhospitable, and traditionally inaccessible environments continues to grow. Foreseeing a need to dramatically miniaturize space vehicle electrical and thermal power management systems, Lockheed Martin (LM) is proving and maturing a small radioisotope thermoelectric generator (RTG) based on an isotope with less handling and launch approval problems than plutonium 238. The RTG generates approximately 100 mW electrical power and 2W of thermal waste heat. Lockheed Martin designed, integrated, and functionally demonstrated concept viability by generating 35 mWe using an electric heat source. Not only does this technology provide continuous electrical power, but it generates thermal energy which can be utilized to reduce the need for dedicated survival heaters.

LM has matured the device to TRL 4 by doing lab testing on the electrically heated devise. This investigation would bring the device to flight ready TRL 6 by late 2022 then fly it as a functioning part of a lunar mission. The development effort will include increasing power generation efficiency through improved component device design and. At the end of 2019 we completed a proof of concept test of our first engineering development unit that produces 35mW of power from a simulated radioisotope heat source. Several design flaws were identified and a second development unit is currently being design which we believe will produce at least twice the power of the original unit. The radioactive heat source will be manufactured then integrated into the completed assembly to enable full environmental and functional testing in flight environments by the end of 2022. For the initial demonstration flight, the mission would be able to use these small heater and power sources to potentially allow the lander or a small science package on the lander to survive the lunar night. 100mW of power will charge a typical cell phone battery in about 2.5 days. That stored energy could then be used to wake up an instrument periodically during the lunar night to gather data for an hour or 2 while the heat is used to keep the instrument above flight allowable temperatures.

High-density High-Frequency Power Electronics for Harsh Environment Applications

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Introduction: Space power distribution systems need a large number of power electronics converters to integrate power generation, enery storage, and various loads. The harsh operating environment, like extreme temperature variation and space radiation, pose a significant challenge on power electronics converter reliability. In order to improve the energy efficiency without excessive radiator for heat rejection, power distribution system is moving toward high-voltage level, e.g. 300 V, which demand more technologies and innovation on power electronics device, packaging, and circuit topology for high reliability operation under high voltage and harsh environment while attaining high density and high efficiency.

Center for Power Electronics Systems (CPES) at Virginia Tech has a long history of research and innovation on high-density high-frequency high-performance power electronics and power distribution system for various industrial applications [1]. The research focuses span from power electronics circuit topologies, to high-density integration and packaging, to power device characterization and reliability evaluations. Over the past years, CPES had built up the unique lab facilities and equipment to conduct critical research topics that affect reliability and life-cycle of wide-band-gap power semiconductor based power electronics system under harsh and extreme operation conditions. As shown in Fig. 1, the packaging lab, device characterization lab and HV testing chamber allows to perform research on power electronics operation at high-temperature, high-altitude, and high-voltage conditions.

Fig. 1. CPES Packaging lab, Device characterization lab, and HV lab

In this presentation, several research activities and major contributions on power electronics for harsh environment are provided, aiming at power electronics systems for future lunar surface power system. Two examples in this abstract are provided as follows.

Radiation Hardened (RH) GaN-based Isolated Dc-Dc Converter:

Enhancement mode GaN FETs have demonstrated superior performance compared to Silicon power MOSFETs when exposed to high radiation. Newly released radiation hardened (rad-hard) GaN FETs not only provide good radiation tolerance, they also provide better figure of merit (FOM) and smaller die sizes compared to current state of the art rad-hard Silicon MOSFETs. In this project, a 400 W isolated dc-dc converter from 100 V to 20 V output for space power system is designed and tested. RH GaN FET is used to replace Si MOSFET. Fig. 2 shows the RH GaN based converter prototype as well as the thermal test results.

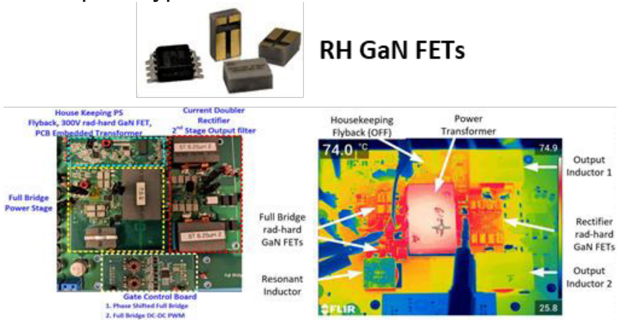

Fig. 2. Isolated RH dc-dc converter and thermal evaluation

High-power Converter and Packaging for Extreme High-temperature (>200°C)

In order to fully exploit the SiC MOSFET high-temperature capability and achieve the best heat rejection performance. A 50 kW high-temperature power module and converter was designed and tested for aerospace applications. As show in Fig. 3. A 200°C rated 120A power module was developed with 1.2 kV SiC MOSFET by considering and choosing the high-temperature packaging materials and layout. Fig. 4 shows the converter prototype with SOIC high-temperature gate-driver, dc-capacitors, and bus-arrays.

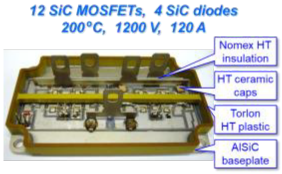

Fig. 3. 200°C power module

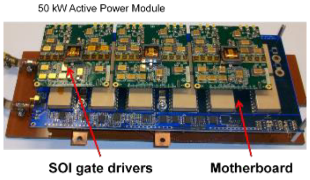

Fig. 4. 200°C rated active rectifier

References:

[1] www.cpes.vt.edu

ICE-RASSOR:
Intelligent Capabilities Enhanced Regolith Advanced Surface Systems Operations Robot

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Abstract: NASA's Regolith Advanced Surface Systems Operations Robot (RASSOR) [1] is principally designed to mine and deliver regolith for In-Situ Resource Utilization (ISRU) processing. RASSOR's design enables it to efficiently collect and deposit regolith, return collected material for processing, and myriad related ISRU activities. To reliably perform these operations on the lunar surface, RASSOR software and sensory systems need to be robust and maximize the information extracted from a reduced sensor payload. Herein, we present preliminary findings from the Intelligent Capabilities Enhanced RASSOR project. We apply supervised learning using real data to estimate the soil mass collected without the need for mass flow rate monitors or other explicate sensing techniques. We also create a reduced-order simulation environment to develop autonomous trenching controllers via reinforcement learning and prototype state estimation architectures. Our initial results suggest that excavated regolith mass can be inferred within 2.9% RMS error of full scale, and reinforcement learning for autonomous operations has learned viable trenching strategies and helped identify desirable sensing capabilities, arrangements, and considerations. Future work includes regolith mass estimation during dynamic operation, expanding our simulation to more complex environments, and transfer learning from simulation to hardware.

References:

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Moon to Mars Planetary Autonomous Construction Technology (MMPACT) Lunar Surface Construction Activity at NASA Marshall Space Flight Center.

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Introduction: The goal of the Moon to Mars Planetary Autonomous Construction Technology (MMPACT) Project at NASA Marshall Space Flight Center (MSFC) is to develop, deliver, and demonstrate on-demand capabilities to protect astronauts and create infrastructure elements on the lunar surface via construction of landing pads, habitats, shelters, roadways, berms, and blast shields using lunar regolith-based materials. MSFC has strong collaborations with industry, academia, and other NASA Centers to accomplish this goal.

The MMPACT project consists of three elements. The first focuses on the development of an autonomous construction system. The second focuses on construction feedstock materials development. The third element focuses on the development of a microwave sintering construction capability.

The team plans to demonstrate construction on a small Commercial Lunar Payload Services (CLPS) lander in the 2025 timeframe, with a future goal of constructing a subscale landing pad in 2028-2029.

The MMPACT project is funded through the Lunar Surface Innovation Initiative, which is part of the Space Technology Mission Directorate.

Technology Development: The MMPACT team will evaluate multiple autonomous construction and microwave construction technologies, materials, and construction element forms. Selected technologies will be matured; processes and operations will be defined for the two flight missions. Evaluations of materials, as well as the technology itself, will be demonstrated in simulated lunar environments as part of the technology maturation process.

The team is keenly aware of the properties of the lunar environment. Its temperature swings, negligible exosphere, and unprepared site foundations factor into the materials for both construction and hardware, the concept of operations, and the technology's interdependencies.

Materials: The team is looking at materials that can be produced from in-situ resources in an effort to make lunar construction cost-effective. The particular focus of the materials team is cementitious materials, metals, and sintered and melted regolith. These materials will be studied for tensile, compressive, and flexural strength. They will also be tested for their ability to handle thermal swings and vacuum. They will be fully characterized using various microscopy techniques to examine microstructures, chemistry, and crystal formation.

Interdependencies: There are many interdependencies that MMPACT has already identified. These include:

- Excavation interface
- Regolith feedstock beneficiation
- Regolith feedstock storage and provision
- Requirements for structures
- Site-to-site mobility systems
- Availability of lunar simulant
- Lander off-loading capabilities
- Navigation systems
- Power
- Regolith composition and mineralogy
- Lander specifications
- Communication protocols

Technology developments in these additional areas would be beneficial to MMPACT.

Building a Cislunar Economy Through Space Resources Utilization (SRU). C.D. Espejel[1,2,3] and J.N. Rasera.[1,4], [1]ispace Europe S.A., 5, rue de l'Industrie, L-1811 Luxembourg City, Luxembourg, [2]University of Luxembourg, 2, avenue de l'Université L-4365 Esch-sur-Alzette, Luxembourg [3]University of New South Wales, Sydney, New South Wales, 2052, Australia [4]Imperial College London, Exhibition Road, London, SW7 2AZ, United Kingdom. (Contact: c-espejel@ispace-inc.com)

Introduction: The number of planned lunar exploration activities by both world-leading space agencies and private companies are indicative of the potential scale of the future lunar economy. Humanity's innate curiosity for exploration and expansion, combined with rapid technological developments, makes the Moon an enticing next step. As history has shown, human exploration activities require new settlements, and new settlements require the use of local resources.

SRU Value Chain: As in the other extractive industries, the extraction and use of resources in space will follow a value chain of activities from exploration to the delivery of a final product. Ispace has developed an end-to-end SRU value chain within which we envision the following steps: project evaluation, exploration, infrastructure development, SRU operations (extraction, processing and refining, storage of final product), and the transportation of finished goods to end users. Supporting services, such as power, communications, etc., would be developed in parallel. ispace will act as an orchestrator of the cis-lunar economic ecosystem, wherein SRU will be a critical component. As a value chain leader, ispace plans to explore, extract and sell essential space resources starting in 2030.

Current Research Activities: ispace understands the importance of all the steps involved in the SRU value chain. As such, ispace is undertaking several key SRU-oriented research projects both independently and in conjunction with world-leading research centres in order to work towards the realisation of the cislunar economy.

Lunar Ore Reserves Standards (LORS). LORS is the first set of frameworks, classification systems and guidelines for the estimation and reporting of space resources, not only for the Moon, but those resources on asteroids and other planets, as well. This framework will be applicable to scientific and commercial entities for both research and economic purposes.

Lunar Dry Ore Enrichment and Recovery System (LunaDORES). In terrestrial mineral processing, beneficiation is a critical step in the flowsheet, and will be important in the lunar context as well [1]. Cilliers, Rasera and Hadler [2] have demonstrated that previous lunar mine scale estimates are undersized due to the omission of the beneficiation step. Dry mineral processing techniques have been proposed for the Moon, however none have progressed beyond the laboratory [3]. The aim of this project is to design and validate a demonstration triboelectrostatic free-fall mineral separator for enriching target minerals on the Lunar surface.

Polar Ice Explorer (PIE) Mission. The goal of the PIE mission is to enhance knowledge of lunar resources and enable future resource utilization on the Moon. The mission consists of a rover equipped with state-of-the-art navigation technology and European science instruments to perform in-situ detection of lunar volatiles and characterize the subsurface. The PIE project is led by ispace Europe with support by the Luxembourg Space Agency. The European Space Agency provides technical and programmatic oversight of the project. The project has recently entered Phase B. The rover will go through a full proto-flight test program and be ready for lander integration in Q1 2023.

Next Steps: Together with our industry and academic partners, are creating an SRU consortium that will focus on several key areas, including: SRU market size and market value; technology development and research to enable the estimated market size and value; and, commercialization of technologies for Earth and space applications. ispace acknowledges that the only way forward to the realisation of SRU is the mutual collaboration of Earth and space industries. ispace advocates for the union of research, resources, and split of risk to achieve the SRU vision.

References: [1] Hadler, K. et al. (2020) Planet. Space Sci., 182, 104811. [2] Cilliers, J.J. et al. (2020) Planet. Space Sci., 180, 104749. [3] Rasera, J.N. et al. (2020) Planet. Space Sci., 104879.

From Mars to the Moon: Lessons Learned from Using the Autonomous Soil Assessment System (ASAS) in the Semi-Autonomous Navigation for Detrital Environments (SAND-E) project.

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Introduction: Semi-Autonomous Navigation for Detrital Environments (SAND-E) is analog science and operations project supported through NASA's Planetary Science and Technology through Analog Research (PSTAR) [1]. The project tests robotic operations for science exploration in environments analogous to those found on the Mars. Part of this project examines the capability and efficiency of automated terrain analysis in science operations. Here, we discuss the technology of the Autonomous Soil Assessment System (ASAS) used to characterize basaltic volcanic terrains and the results of its deployment during a scientific investigation.

Methods, Study Area, and Technology: Six operational scenarios were tested during field operations in Iceland with a team of ten scientists and five engineers. The scientists were in simulation without knowledge of the field area in order to maximize the operations testing fidelity. Engineers drove the rover based on input from scientists and feedback from ASAS.

ASAS is a software-based system that comprises advanced image processing and machine learning technologies for two functions [2]. First, it classifies terrain types from a rover's navigation camera (Mars e.g., sand ripples, bedrock, clay; Moon e.g., craters, rocks, regolith tone) using deep learning models, in semantic segmentation fashion. Second, it builds a data-driven trafficability model in real-time using a rover's standard navigation sensors; this is a model of wheel slip against terrain slope for a specific terrain type, which is then used to classify a hazard heuristic (high, medium, low). Together, ASAS enables a way to intelligently characterize terrain types and mobility hazards using the rover's own data. This can be used by onboard algorithms like path planning, or can be used as a ground operations support tool.

Results and Discussion: ASAS was tested during three operational scenarios in which the scientists had access to optical images, which had been pixelwise segmented by geological terrain type and terrain hazard (Fig. 1A and 1B).

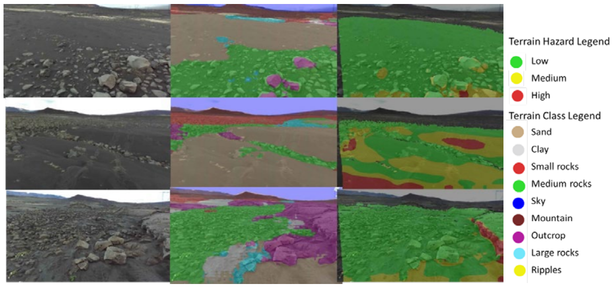

Figure 1 Example ASAS data from Iceland (left) optical image, (middle) ASAS terrain classification, (right) ASAS hazard classification

The segmented images proved most valuable during a walkabout-type scenario, during which the rover semi-autonomously traversed a field area and returned segmented images to the scientists. By clicking through the segmented images in movie-like fashion, the scientists were able to evaluate the distribution of terrains and identify potential targets more quickly and easily than using the optical images alone. During a more typical Mars rover operations-type scenario the segmented data were used less frequently. The scientists reported cognitive overload in trying to incorporate the segmented data with other downlinked science data. This experience suggests that autonomous terrain analysis for science may be most useful for time-sensitive exploration focused on rapid decision making for scientific targets. Such scenarios will be needed for exploration and prospecting on the lunar surface in preparation for mining activities and infrastructure development.

To the Moon: For lunar exploration, Mission Control is adapting the terrain classifier from ASAS to build a lunar science autonomy system named ASAS-CRATERS (Contextualizing Rocks, Anomalies and Terrains in Exploratory Robotic Science) [3]. The ASAS trafficability system will also be adapted for lunar exploration. Mission Control is targeting demonstrations in upcoming lunar missions in 2022 and 2023, and will showcase how its software can augment science and navigation autonomy for resource-constrained mobility platforms that access and explore extreme environments.

References:

[1] Ewing, R.C., et al., (2019) American Geophysical Union Fall Meeting, Abstract #EP24A-05.

[2] Faragalli M. et al. (2018) *i-SAIRAS*.

[3] Raimalwala, K. et al. (2020) *Lunar Surface Science Workshop*, *LPICo* 2241, p5124.

PlanetVac: Sample Acquisition and Delivery System for Instruments and Sample Return.

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Introduction: PlanetVac is a revolutionary technology for acquiring and transferring regolith from the lunar surface to instruments (for in situ analysis) or sample returned container (for sample return missions) [1].

PlanetVac uses robust and dust tolerant pneumatic approach, similar to traditional pneumatic based powder delivery technologies used on earth. The main difference is the sources of gas: PlanetVac uses a standalone gas canister to provide working fluid.

PlanetVac spacecraft accommodation: PlanetVac, in the base scenario, is attached to a footpad (or footpads if more than one PlanetVac is used) of a lander and is connected to instruments or sample return containers via a pneumatic transfer hose. Hence the exact location of the instruments and sample container is irrelevant since the transfer hose can be routed around other systems. The sample is acquired within seconds, with virtually no power. The only command is a signal to open gas valve connected to a tank.

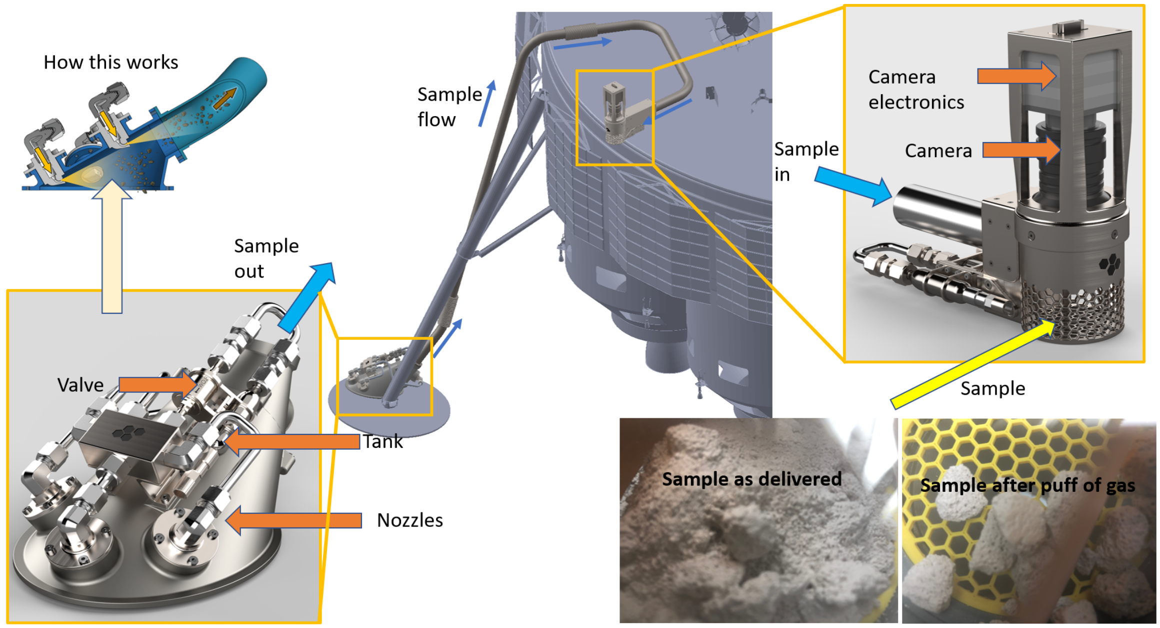

Figure 1. PlanetVac pneumatic sample delivery.

As illustrated by numerous surface missions (Viking, Mars Phoenix, MSL Curiosity, Venera, Luna etc.) sample acquisition and delivery is one of the most difficult aspects of the mission. In fact, several missions (e.g. Venera) did not meet their scientific goals because of sample delivery system failure, while other missions (e.g. Phoenix) had not utilized the entire instrument suite because of difficulty in sample delivery.

The technology has been demonstrated on reduced gravity flights at lunar gravity and vacuum. The technology has been demonstrated in delivering samples (fines as well as rocklets) to various instrument cups [3]. The technology has also been demonstrated on actual lander: Masten Xombie during tests in Mojave, CA [2].

LISTP: For LSITP, PlanetVac will deliver lunar regolith and demonstrate sieving of the lunar regolith in the sample return container (Figure 1). The regolith will be split into fines and rocklets. Sample delivery verification will be done with a camera.

Acknowledgments: The funding for this work has been provided by the NASA SBIR, SpaceTech REDDI and The Planetary Society.

References: [1] Zacny et al., (2014), PlanetVac: Pneumatic Regolith Sampling System, IEEE Aerospace Conference, 3-7 March 2014, Big Sky MT, [2] Spring et al., (2019), PlanetVac Xodiac: Lander Foot Pad Integrated Planetary Sampling System, IEEE Aerospace Conf., [3] Zacny et al., (2019), Application of Pneumatics in Delivering Samples to Instruments on Planetary Missions, IEEE Aerospace Conf., 2-9 March 2019, Big Sky, MT.

Dust Solution Testing Initiative (DuSTI): Infusing Commercial Off the Shelf Dust Mitigation Technologies with NASA Practices.

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Introduction: Dust is one of the most significant hazards to human lunar exploration. However, since the Apollo program concluded, limited research has been performed on lunar dust mitigation technologies. The safety of the crew members and sustainability of habitats, science, and supporting hardware depend on effective dust mitigation techniques and technologies. As NASA pursues a new generation of lunar missions with the Artemis program, the project team will pursue dust mitigation solutions with the Dust Solution Testing Initiative (DuSTI). DuSTI is a lunar dust mitigation effort that involves performing tests on commercial off the shelf (COTS) technologies over FY21.

DuSTI will preform component and subsystem tests in dusty environments for up to five technologies with high potential. The specific technologies identified for study were selected based on several factors, including a market analysis of current terrestrial dust mitigation applications, availability of the technology, accessibility of various testing facilities, and cost of procurement. These technologies support the active and passive dust mitigation requirements of filtration systems, electro-mechanical systems, electro-static systems, surface coatings, textiles, and silicone polymers. Technology Readiness Level (TRL) will be increased by validating components in relevant environments. For example, if the COTS technology is at a TRL 9 for terrestrial use but at a 4-5 TRL for use in the lunar environment, we will test that technology in a lunar dust environment to increase the TRL for use on the Moon.

Technology Gap: The current need for NASA to have effective dust mitigation technologies stems from its human exploration mission plan to return to the lunar surface in 2024 with continued surface missions throughout 2030, including permanent habitation in the next 10 years. NASA's official lunar dust mitigation strategy will implement a three-pronged approach: operational and architecture considerations, passive technologies, and active technologies [1]. DuSTI will contribute to all three components.

Gap 1: Commercial Availability. With the return to the lunar surface being announced recently, the need for dust mitigation techniques has increased, but the availability of dust mitigation technologies for reduced gravity and micro-atmospheric environments is still limited due to the lack of lunar missions after the Apollo Program terminated in 1972. Without the demand, the focus for dust mitigation became limited to consumer appliances, construction and military aircraft landings in desert environments. Successful testing of commercially available dust mitigation methods in a simulated lunar environment alleviates the challenges associated with research, testing, production, and application of these methods. This allows NASA engineers to focus specifically on testing and application which preserves resources like funding, labor and time for developing aspects of the 2024 lunar mission.

Gap 2: Uniqueness of Environment. Most commercial companies providing dust mitigation technologies test their products based on the environments and particulates encountered on Earth. Testing of these COTS technologies in a simulated lunar mission environment must be conducted to determine if they can support the changes in pressure, temperature, and solar radiation both inside the pressurized vehicle, EVA suit or habitat, and outside of the vehicle, on the lunar surface or in orbit. It is also vital to test with the dust/regolith simulant particulates that have been created to replicate the aspects of the lunar regolith needed for testing.

Future Work: The results of DuSTI testing will be compiled into a technology infusion report in Q4 of FY21 and each year the project is funded. These technologies will be tested using NASA JSC/KSC/GRC and Air Dynamics test facilities designed to simulate the lunar environments that are expected during the upcoming Artemis missions. DuSTI is aligned to improve upon modern methods of lunar dust mitigation in a variety of lunar surface mission environments,setting the stage for astronauts to address dust mitigation challenges for sustained lunar presence.

Acknowledgements: DuSTI would like to thank the Center Innovation Fund Independent R & D at NASA Johnson Space Center for funding. DuSTI would also like to thank Chris Alkire for initial project management and project development support.

References: [1] Johansen M. R. (2020) *Lunar Dust Workshop, No. 2141.*

Lunar Landing and Launch Pad Construction – Concepts and Criteria

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2 Langley Research Center, National Aeronautics & Space Administration (NASA), Mail Stop 489, Hampton, VA 23681, USA
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4 Swamp Works, The Bionetics Corp., LASSO-013, Kennedy Space Center, FL 32899, USA
5 Swamp Works, Southeastern Universities Research Association (SURA), LASSO-013, Kennedy Space Center, FL 32899, USA

Introduction: When a lander vehicle launches or lands on the Moon, the rocket engine exhaust plume impinges on the surface and interacts with the regolith to create blast ejecta and associated cratering of the surface. Lunar regolith blast ejecta travels at high velocities (>2,000 m/s) for long distances (kilometers) in a vacuum environment [1] creating hazards for surrounding assets and it can also impact the bottom of the lander vehicle, risking damage to the engines, thermal insulation and sensors. Ballistic particles can possibly enter cislunar space and achieve orbit as debris, if the ejecta is sufficiently energetic. The cratering and regolith erosion can endanger the vehicle itself by affecting the soil stability under the landing gear. Landing on unpredictable terrain with varying topography, natural craters and rock hazards is also hazardous risks tipping a lander at dangerous angles in extreme conditions that may also violate maximum slope angles for subsequent launch operations. During launch (Figure 1), an overpressure pulse created by the ignition of the rocket engines can pose significant ejecta risks to the vehicle. Dust clouds raised during landing limit the efficacy of sensors and reduce visibility for the astronaut pilots, creating significant real-time risk during landing site selection by the pilot or computer navigation system. Future lunar spaceports will require mitigations to these launch and landing risks [2].

There are four main objectives of this effort: 1) To establish the state of the art in LLP construction methodologies. 2) To propose criteria for trade studies of LLP concepts. 3) To publicly share the authors' ideas for potential LLP solutions. 4) To serve as the starting point for future development of LLP technologies.

Establishing the state of the art in the area of off-Earth Launch & Landing Pad concepts will baseline the work that has been completed thus far and highlight the wide span between current Technology Readiness Levels (TRLs) and operational readiness. The authors aim to communicate the need for funding in this area in the near term by illustrating that there is much work to be completed before a truly viable option exists.

Setting forth criteria for trade studies of LLP concepts is important for several reasons. The first and most straightforward is to establish a framework for performing trade studies on LLP concepts. This will enable NASA to select the most promising concepts for continued development, and it will also help technology developers understand how their concepts compare with others and the priorities of development efforts.

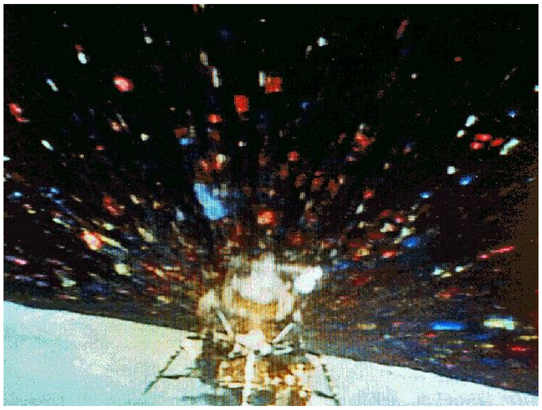

Figure 1. Apollo 16 ascent stage liftoff showing extensive ejecta debris (NASA PHOTO: s72-35613.)

References: [1] Lane, J.E., & Metzger, P.T. (2015). "Estimation of Apollo lunar dust transport using optical extinction measurements." Acta Geophys., 63 (2), 568-599. [2] Benaroya, H., Bernold, L., & Chua, K.M. (2002). "Engineering, design and construction of lunar bases." J. Aerosp. Eng., 15(2), 33-45.

A Large Thermal-Vacuum-Plasma Facility to Simulate Lunar Extreme Environments. D. Han[1], H. Pernicka[1], and Leslie Gertsch[1], [1]Missouri University of Science and Technology, 1870 Miner Circle, Rolla, MO 65409. (Contact: handao@mst.edu)

Introduction: The Missouri University of Science and Technology (Missouri S&T) in Rolla, MO has a large (thermal)-vacuum-plasma facility to simulate lunar extreme environments (vacuum, solar wind plasma, and thermal cycles). The technical capabilities of this facility provide a platform for research and development efforts in several LSIC technical focus areas.

Large Vacuum Facility: The Mechanical and Aerospace Engineering department's Gas and Plasma Dynamics Laboratory houses a large vacuum facility including a 6-ft (1.8-m) diameter, 10-ft (3.0-m) long vacuum chamber evacuated using four diffusion pumps, as shown in **Fig. 1 (left)**. This setup provides an estimated pumping speed of 200,000 L/s on air (250,000 L/s on H2, 50,000 L/s on Xe). A high throughput roughing pump with a roots blower is used to initially evacuate the system to rough vacuum (~100 mTorr). The diffusion pumps are then activated to attain high vacuum (base pressure ~1 x 10^{-7} Torr). A series of valves are used to open and close the pumping system from the vacuum chamber. Pressure sensors and measurement instruments are used to monitor the status of the facility.

Figure 1: (left) The large vacuum facility. (middle and right) The plasma source.

Plasma Source: The plasma source is a 12-cm radio-frequency source installed in the vacuum chamber **(Fig. 1 (middle and right))** [1]. The source can generate an ion beam with kinetic energy of up to 1. 5 keV with maximum beam current 500 mA. It is capable of continuously operating for days without changing the neutralizer.

Thermal-Cycling System (planned for 2020-2021): Planned facility/equipment upgrades through a recent FY 2020 award include a thermal-cycling system with heating/cooling capabilities to simulate the space/high-altitude thermal environment. The planned temperature range is from -190 °C (through liquid nitrogen) to 150 °C (through distributed radiant heaters), or 83 K to 423 K.

Diagnostic Systems: The diagnostic systems include a suite of probes for plasma; pressure sensors; as well as thermal couples (expected in 2020).

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

[1] Folta et al. (2020) *AIAA 2020-0048*.

Effects of Percussion on Lunar Regolith Excavation Forces. S. Indyk, K. Zacny, G. Paulsen, P. Chu, J. Spring, Honeybee Robotics, 2408 Lincoln Blvd., Altadena, CA 91001, (zacny@honeybeerobotics.com)

Abstract: The purpose of vibratory and percussive scoops is to reduce excavation forces during material acquisition and to allow easier discharge of material during material gravity transfer - something that was witnessed during operation of Mars Phenix scoop [1]. Vibration (as opposed to percussion) occurs when the motion is in a particular direction without any impacts. This is akin to a sonic toothbrush. Percussion occurs when there is an impact onto the blade – e.g. jack hammers that are used to break up concrete. Using percussive scoops is not new, some commercial hammer drills include a scoop as an attachment. To use these scoops, the hammer drill is switched to hammer-only mode.

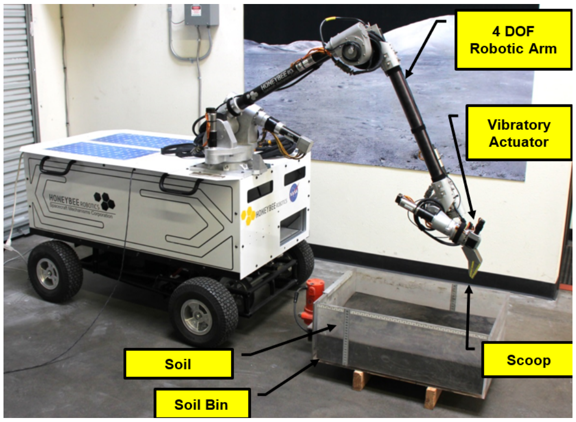

Figure 1. A Surveyor-style vibratory scoop mounted to a robotic arm on Honeybee's mobile test platform.

An experimental setup testing two percussive scoop systems was tested in lunar simulant and is shown in Figure 1. The scoop used a simple brushless DC motor to power an offset mass by way of a pair of helical gears. Two slightly different designs were used, whereby the plane of vibration of the offset mass was oriented differently relative to the direction of scooping. Figure 2 shows a model of the two scoop designs and test data. The scoop used for these excavation tests is similar to the scoop used by the Lunar Surveyor mission. Using similar geometry facilitates more meaningful comparison with the Surveyor data, as well as with tests performed by others using the same or similar geometry. Excavation tests were performed in JSC-1, a lunar mare simulant.

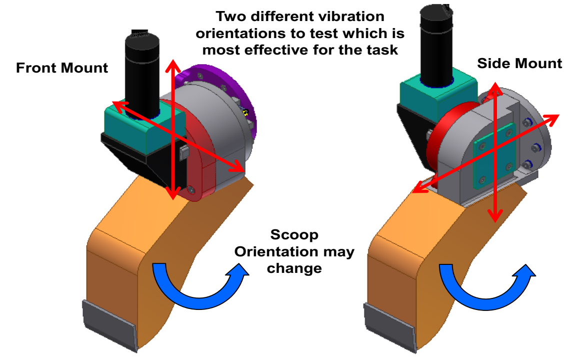

Figure 1. Vibratory Scoop Design

The shear strength of a soil is dependent upon three critical factors: the cohesion, the effective stress, and the internal friction angle. The magnitude of the internal friction angle is based on two different components: surface-to-surface sliding friction and soil particle relative movement, which is known as dilatancy. When percussion is applied to an excavator implement in dry JSC-1A soil, at the proper frequency and impact energy, the magnitude of dilatancy is reduced. A reduction in soil dilatancy causes the shear strength of the soil to decrease. The decrease in soil strength is made manifest through a reduction in the baseline excavation draft force and an alteration in the defining geometry of the tool-soil failure volume. The manner in which percussion influences soil strength is dependent upon several variables. Six variables were examined in this work: percussive frequency, percussive impact energy, excavator speed, excavator depth, angle of attack, and in-situ relative density [2].

Due to the plausibility of reducing in-situ soil shear strength, future low gravity excavator designs do not have to be constrained to the high body forces required in static excavation. The analysis provided in this work gives information regarding which parameters are most critical in the design of future percussive systems.

References: [1] Zacny et al., (2009), Percussive Digging Approach to Lunar Excavation and Mining. Annual Meeting of LEAG and SRR, Houston 16-19, Nov 2009. [2] Green et al., (2013) Investigating the Effects of Percussion on Excavation Forces. ASCE.

Developing complex algorithms to characterize water-bearing lunar regolith at cryogenic conditions.

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Introduction: With the recent push from the space community on lunar ISRU, the uncertainty related to lunar water-ice in the permanently shaowed region (PSR) has become a roadblock in efficienty exploring the Moon.. The only way to reduce this uncertainty is by undertaking an extensive exploratory drilling program to access and test subsurface regolith and water-ice samples. This work discusses development and testing of a complex pattern-recogntiion algorithm which can be used to tacked some of the uncertaines mentioned above. Such algorithms has been used to identify the subsurface layers, form of the water-ice, and estimate uniaxial compressive strength (UCS) an d water-content. The algorithms were tested on analog samples at lab environment and on different forms of water-ice bearing lunar regolith simulant samples at cryogenic conditions.

Experimental Setup: A test drilling unit was designed and fabricated to acquire high-frequency drilling data from both analog and cryogenic samples and a cryogenic setup was fabricated to contain a sample and cool it down to -190℃ ([2], [3]). The drilling tests were conducted on four different forms of water-bearing lunar regolith simulants at cryogenic conditions: low-porosity aqueous icy, high-porosity aqueous icy, fused granular icy, and unfused granular icy samples. Figure 1 shows the drilling rig setup with the cryogenic testing setup.

Figure 1: Drilling tests being conducted on cryogenic samples.

In total, drilling data from 87 boreholes was recorded out of which, the data from 80 boreholes (~ 1 billion data points) was used to train and validate the pattern recognition algorithm. The pattern-recognition algorithm comprising of three classification and two regression algorithms were trained and validated before deploying it on the cryogenic samples.

Results: The algorithms were tested to detect boundaries for layered samples, differentiate between high-porosity and low-porosity samples, identify the form of the sample, and calculate UCS.

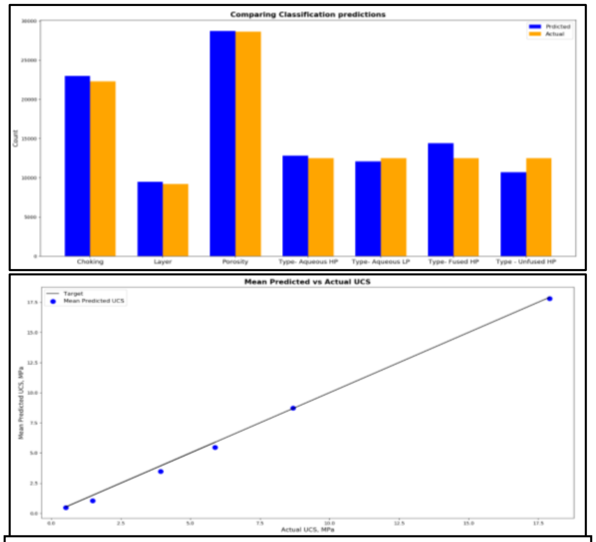

Figure 2: (top) Comparing the predicted auger choking, layer boundary, sample porosity type, and sample type for blind cryogenic data and (bottom) compares the mean predicted UCS with actual UCS. Both predictions were made over 100,000 data points.

Figrue 2(top) shows the performance of the algorithm to detect auger choking, porosity of the sample, layer boundary. The algorithm identified these accurately for 98% of the data points. Figure 2(top) also shows the performance of the algorithm in detecting the form water-bearing regolith. Here the algorithm accuracy is 93%. Figure 2(bottom) shows the performance of the final pattern recognition algorithm in estimating UCS of the sample. Such versatile algorithms can be invaluable to expand capabilities of drills like TRIDENT to better understand subsurface lunar properties.

References: [1] Nean, C. (2018), Space Resources Roundtable. [2] Joshi et al. (2020a) SPE-199684-MS. [3] Joshi et al. (2020b) AIAA ASCEND 2020.

This work was supported by an Early Stage Innovation grant from NASA's Space Technology Research Grants Program Grant No 80NSSC18K0262.

Feasibility Study of a Novel Electrostatic Transportation of Sublimated Vapor and High Capacity Cold Trap with Engineered Cryogenic Heat Pipe to Re-Capture Ice In a Low-Pressure Condition

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Introduction: The ongoing “Lunar Resource Development: Rarefied Water Vapor Ionization and Condensation” project between NASA Johnson Space Center and UTEP cSETR [1] is focused on the design and development of experimental hardware to transport sublimated water vapor from thermally mined lunar regolith and characterization of water collection rates in a condensation chamber (Fig. 1). The sublimated water vapor from the lunar regolith from existing thermal mining technologies such as thermal drills, solar concentrator dome heaters exhibit ultra-low pressure [2], therefore, makes it difficult for the rarefied vapor to transport to the ice collection chamber. Moreover, the poor thermal conductivity of lunar regolith imposes high temperature heating which results in generation of other volatiles. Thus, the separation of other volatiles from the required water vapor is another challenging issue in lunar water collection technology. Once the vapor molecules reach the condensation chamber, another challenge sustains in the re-collection process is the poor thermal conductivity of ice. The only available modes of heat transfer in lunar conditions are only by conduction through the accumulated ice and the condenser wall, and then rejection to the ambient (~ 25 - 40 K) via radiation.

Therefore, this work presents an advanced water vapor separation and transportation using electroststic field-induced pathway, and a continuously ice re-capture technology in an active condenser chamber that utilizes heat pipe as an condenser plate, a thin film negative electrode to attract the ionized vapor meolecules, and thin film vapor producing heater for intermittent delamination of ice film.

Ionization and Electrostatic Transportation of Sublimated Vapor to the Cold Trap: The engineered vapor transportation system focuses on vapor ionization and transportation of the water vapor (Fig. 1) sublimated from LMS-1 simulant to the condenser chamber. Three ionization transport methods were considered in this work: (i) a tungsten filament electron emitter, (ii) a radio-frequency plasma source, and (iii) a tungsten filament with applied magnetic field for electron trapping. Analytic estimates based on a laboratory scale experiment suggest up to a 450% increase in water collection rates using ionization transport methods.

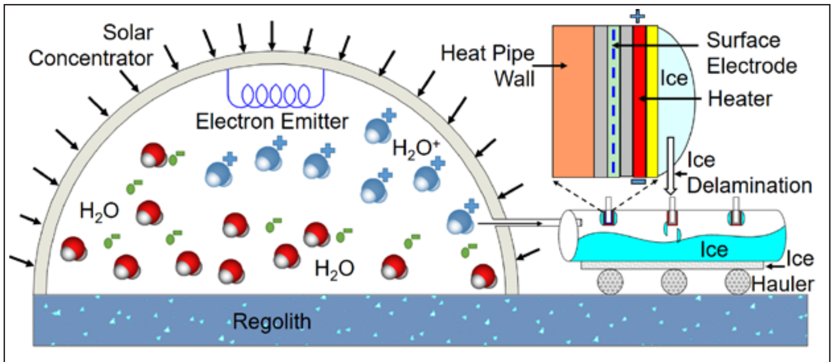

Figure 1: cSETR advanced thermal mining technology

The experimental tests were performed in the cSETR Thermal Vacuum (T-Vac) Chamber at 10^{-6} Torr and -120 °C.

High Capacity Cold Trap with Engineered Cryogenic Heat Pipe for Lunar Ice Collector: The high capacity engineered cold trap focuses on developing a space-qualified engineered cryogenic heat pipe and collecting ice in a cold trap from lunar regolith during thermal mining. An analytical heat transfer analysis suggests that a 35x ice accumulation capacity can be achieved using intermittent ice delamination as compared to continuous deposition. To identify the rarefied vapor deposition fundamentals, this work fabricated a custom-built cold plate (up to -130 °C) and tested the ice deposition in vacuum pressure (10^{-5} Torr) with 1×10^{-7} kg/m^2-s vapor mass flux. The engineered cold plate consists of an electrode to attract the ionized vapor and a thin film resistive heater to intermittently generate thin vapor fim between the cold plate and the bulk ice, and facilitate the ice delamination.

In Summary, this work demonstrates an efficient high capacity vapor transportation and collection system for advanced lunar thermal mining.

References: [1] NASA JSC and UTEP cSETR Alliance for Lunar Resource Development-CAN 80NSSC20M0011, [2] K. Zacny et al., Honeybee Robotics, NASA JSC, Planetary Science Vision 2050 Workshop 2017 (LPI Contrib. No. 1989)

POCCET: A Compact Cleaning Tool For Miniature Planetary Rovers.

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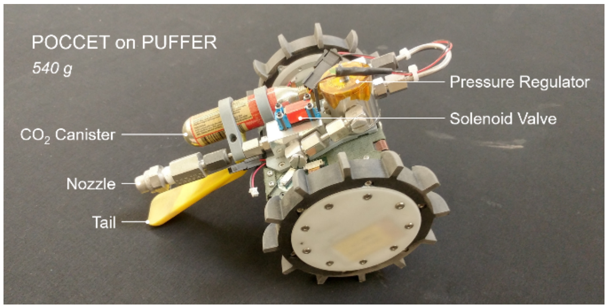
Abstract: A major problem in space exploration is dust contamination. Dust covers rock samples and makes it difficult for rovers to take accurate in-situ measurements. Onboard instruments such as cameras and spectrometers (e.g. APXS [1]) require relatively clean surfaces in order to make meaningful measurements of their target samples. In addition, dust prevents equipment such as camera lenses and solar panels from working efficiently. Due to these problems, there is a need for dust removal tools that are effective on a wide range of surfaces.

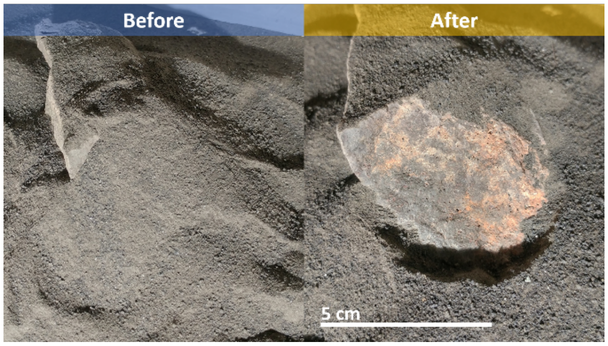
To meet this need, Honeybee Robotics developed POCCET (PUFFER-Oriented Compact Cleaning and Excavation Tool), a small tool that can be mounted on miniature robots to remove regolith from natural and artificial surfaces. POCCET is based on a simple and robust pneumatic architecture. Liquid carbon dioxide is stored in an onboard canister to provide greater than 800 psi vapor pressure at 20°C. Downstream of this tank, a pressure regulator reduces the gas pressure to 40 psi, and a microfluidics solenoid valve controls the flow of gas out of the system. A nozzle at the outlet shapes the flow of gas and consequently the geometry of the cleaned surface.

A POCCET prototype was built, integrated, and tested with one of JPL's latest PUFFER prototypes [2]. Tests were conducted under soft vacuum conditions (~10 Torr) to demonstrate POCCET's ability to clean lunar regolith simulant (JSC-1A) off vesicular basalt rock samples and a solar panel. On a horizontal surface, POCCET can clean off a layer of dust 10 mm deep and ~15 cm^2 in area in six seconds. In addition to cleaning dust off surfaces, POCCET can be used to trench through regolith to expose near-surface lunar ice. While this iteration of POCCET was designed to interface specifically with PUFFER, a similar system can be built and integrated into nearly any exploration vehicle.

The POCCET prototype carries enough CO_2 to support approximately 24 seconds of nominal cleaning operations. During this time, the volumetric flow rate is steady and cleaning performance is relatively consistent. Subsequently, the flow rate will begin to decrease as the tank is depleted. POCCET can continue to be used with this reduced flow, but the cleaning performance will eventually suffer. In testing, POCCET utilizes a nominal burst duration of six second, and can execute four full cleaning operations. However, this cleaning duration can be adjusted based on the expected amounts of dust or decreased to prolong the useful lifetime of the tool.

This iteration of POCCET was intended as a proof-of-concept prototype and uses commercial off-the-shelf hardware. The prototype weighs 280 g, compared to PUFFER's 270 g. With POCCET mounted on top, PUFFER remains mobile, but trafficability on steeper slopes is noticeably diminished. A flight-like POCCET design would use custom hardware and has the potential to be significantly lighter and more compact. With this initial POCCET prototype, Honeybee Robotics successfully demonstrates the feasibility and usefulness of a compact cleaning and excavation tool for miniature planetary rovers.





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Power Beaming for Lunar Polar Exploration

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Systems to provide electrical power are critical for both robotic and human lunar polar operations. The south polar region, for example, has been baselined as landing site for NASA Artemis human exploration. The fact that the complete absence of sunlight means conventional solar power systems cannot operate in the scientifically-interesting permanently-shadowed craters is a significant technology challenge to be addressed for NASA's future exploration. This has been specifically identified in the NASA Space Technology Mission Directorate (STMD) Strategic Thrust D, "Sustainable power in extreme lunar surface environments".

Recent advances in technology now present a possible approach to addressing this problem: to beam power directly from a power source (either a solar array or a nuclear reactor) at the illuminated rim of such a crater to receiver that converts the beamed energy to electrical power to recharge a rover exploring inside the shadowed region. Power beaming has been proposed before, but there has not previously been a compelling mission application for the capability. The current NASA objective of developing technologies for lunar polar exploration provides the need, and the evolution of higher-power and more efficient power transfer and receiving systems provides the opportunity.

Several different technologies are possible for such power beaming. Lasers, microwaves, and millimeter waves all have been proposed, with advantages and disadvantages to each technology, depending on the details of the mission concept.

Development of this technology is currently a topic of the NASA Lunar Surface Technology (LuSTR) research program, part of the NASA Space Technology Research Grants Program.

The gap to be addressed between needs and capability is that while such systems have been proposed, a demonstration of power transfer at high enough power to operate a rover will be critical before any such system can be used on the moon. To move this technology from the conceptual design to a system that can be implemented for exploration, it will have to be demonstrated, both with ground- and space-based prototype systems. The project goal is to develop and demonstrate this capability: surface to surface power beaming, at a level capable of powering a lunar rover.

Centrifugal Molten Regolith Electrolysis (MRE) Reactor for Oxygen, Volatiles, and Metals Extraction

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Abstract: A novel rotating shell and drum molten regolith electrolysis (MRE) reactor is proposed to electrochemically decompose, while under centrifugal action, lunar regolith into oxygen, metals, and semiconductor materials [1]. The proposed continuous-feed reactor design provides a viable alternative for enhanced in-situ resource utilization (ISRU) on the Moon. In my proposed reactor design, the traditional tightly spaced “multi-stack” parallel square plate or circular disc electrode cell configuration (associated with conventional electrolysis cells) are replaced in favor of a new type of rotating cylindrical cell design – a new type of cell design that, unlike conventional multiple stack designs (with their concomitant O_2 transport and removal problems), consists of only two large surface area cylindrical electrodes (sawtooth ~5 m^2 each); namely, (1) an outer rotating cylindrical shell that serves as the cathode (and as the reactor containment vessel), and (2) an inner concentrically positioned drum that serves as the anode.

In this novel configuration, and because the shell and concentric drum are rotating about a central tube, regolith introduced into the top of the rotating reactor (through an upper part of the central tube) will be flung against the inner wall of the outer shell where it will be rapidly melted. The outer shell (and inner drum) will be made of refractory metals; and, as such, the outer metallic shell may be heated inductively (by means of a surrounding stationary induction coil). The supplemental heat energy provided through selective electromagnetic induction heating (in addition to the Joule heating provided by electrolysis) will aid in regolith melting, flowability, and temperature control.

In addition, and to facilitate rapid melting of the regolith (and to ensure superior metal reduction and separation), small amounts of a suitable fluxing/thermite agent will be admixed with the regolith feedstock (in an estimated amount of about 1-part fluxing/thermite agent per 100,000 parts of regolith). After melting, electrolysis begins when the molten regolith flows downwardly along the inner shell wall and into the annular space existing between the outer shell (cathode) and its inner counterpart drum (anode), which is the electrolysis zone. During electrolysis and because of the centrifugal action, the denser liquid metals reduced at the outer cathode will form a thin liquid metal layer against the shell wall (thereby protecting the metallic shell from oxidation), whereas the oxygen evolved (at the inner anode) will be efficiently removed from the anode (through rows of anode through-holes) and vacuum drawn inwardly and into a lower part of the central tube (and out of the reactor for subsequent liquefaction and storage).

The rotating and downwardly flowing liquid metal layer (consisting essentially of Fe, Si, Al, and Ti) reduced via electrolysis will then be separated from the unreduced and less dense remaining oxide slag overlayer by means of a concentric stationary splitting ring. The stationary splitting ring will be concentrically positioned at the bottom of the electrolysis cell roughly halfway between the outer cathode (shell) and the inner anode (drum). In this configuration, the separated layers of liquid metal and molten slag will then be collected in separate underneath reservoirs formed within the interior part of a stationary doughnut-shaped base.

Specifications, Energy Requirements, Products:

Inputs and energy requirements [2],[3]

Feedstock = Lunar regolith (unprocessed)
Reactor size: H = 1.8 m, D = 0.9 m
Feed rate = 1,000 kg/24hrs (~11.5 grams/sec)
Residence Time = ~90 min
Rotary velocity = ~8 – 12 m/sec
Operating temp. = ~1450 – 1650°C
Melt cond. = ~0.08 cm^{-1}ohm^{-1} – 1 cm^{-1}ohm^{-1}
Electrode (sawtooth) area, A = ~5 m^2 each
Electrode spacing, L = 0.635 cm
Electric potential energies = -0.7 V to -2 V
Oxygen production efficiency = ~60-90%
Total energy required = ~4-5 MWhr/170 kg O_2

Output products (per 1,000 kg of regolith/24hrs)

O_2 production = ~170 kg; Volatiles = ~0.1 kg
Metals production: Fe = ~194 kg
Si = ~162 kg
Ti = ~13 kg
Al = ~1 kg
Total metals production = ~370 kg
Total slag production = ~460 kg
Standard brick size = 3⅝” x 2¼” x 8”
Total # of hot metal bricks produced = ~90
Total # of hot slag bricks produced = ~125

References:

[1] T. E. Loop, U.S. Pat. Appl. No. 17/013,584 (2020).
[2] R. O. Colson, L. A. Haskins, *Space Resources* (1992).
[3] L. A. Haskins et al., NASA conference paper (1992).

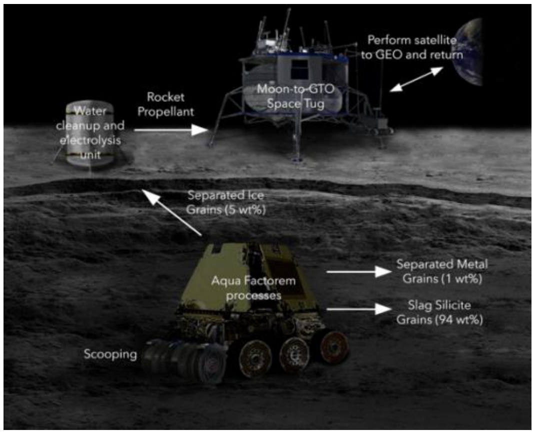
Aqua Factorem: Dramatically Reducing Energy and Infrastructure Cost to Extract Lunar Ice.

P. T. Metzger[1], D. Sapkota[1], A. St. John[1], and E. Smith[1]. [1] Florida Space Institute, University of Central Florida, 12354 Research Pkwy Ste. 214, Partnership I Bldg., Orlando, FL 32826. (Contact: philip.metzger@ucf.edu)

Introduction: Most concepts of extracting lunar ice are based on phase change in the Permanently Shadowed Regions (PSRs), but this requires a vast energy budget, driving the architecture to include massive energy infrastructure that will have high cost for development, deployment and maintenance. It will likely take decades to perfect such large-scale operations to reduce the need for on-site human laborand make the operation economically viable. The risk-cost relationship deters private investment, which militates against NASA's intention of Sustainable Exploration, having multiple customers so that NASA does not need to bear the entire cost of space infrastructure. Ice extraction methods that reduce energy demand are highly leveraged to improve this situation.

Extraction by Beneficiation: An alternative to phase change is to excavate regolith and perform beneficiation to sort the solid phases on the basis of their composition. Beneficiation is routinely used in terrestrial industry. We innovated a patent-pending method to beneficiate ice from regolith by using a combination of grinding, pneumatic separation, magnetic separation, and electrostatic separation. This will reduce exacavated mass by 95-98%, making it feasible to haul the resource from the PSR to sunlight for further processing. This can produce a 99% energy reduction in the PSR, and the remaining energy need can be satisfied by simple methods such as carrying regenerable fuel cells along with the resource. This produces such a simple architecture that a pilot plant can fit onto a single lander. It is scalable, so mining can be perfected at small scale then throughput can be increase simply by adding more of the mature assets. This creates a vastly better cost-risk scenario for investors, produces revenue from the earliest operation, and buys-down risk incrementally as throughput increases. Other assets can be added to the architecture to extend the reach into deeper PSRs for higher yield, but that is after most risk has been retired so it will be economically feasible.

Beneficiation Process: Geological modeling [1] and observational data [2-3] indicate the ice is crystalline and fine-grained in the 10-100 μm size range matching the lithic grain size. This makes sense since ice is just another mineral at PSR temperatures [4] and the micrometeoroid environment comminutes crystalline solids to that range. There may be reworking through vapor diffusion and refreezing inducing cementation in the soil including necking of ice between lithic grains. However, that process does not occur with lithic material (although they are vaporized in the gardening process) and LCROSS indicated the target soil was weak and highly porous (5-10% water ice) so it is unlikely any cementation is significant. Grinding fractures along crystalline grain boundaries, so bound ice can be separated and beneficiated along with ice that is already free granular. Pneumatic separation relies on ballistic coefficient which is a factor of ~3 different for ice than lithic material. Magnetic sepration has high throughput and is 6 times more effective separating paramagnetic minerals from ice in the PSR temperatures than at terrestrial ambient according to the Curie-Weiss law. Ice tribocharges but does so much differently than mineral particles. All three methods are highly effective and in combination can produce high throughput with a goal of complete separation.



Project Status: The technology is at TRL-2 and was awarded a NIAC grant that will finish demonstrating TRL-3 by January 2021. Bench testing is in progress. A prototype is being fabricated to perform demonstrations on a rover.

References: [1] Hurley, D. M., *et al*., Geophys. Res. Lett., 39 (9), (2012). [2] Li, Shuai, L., Milliken, R. E.. *Science Advances*, 3 (9), e1701471. [3] Colaprete, A., et al.. " LEAG 2015, Abstract #1608,https://kiss.caltech.edu/workshops/lunar_

A Regime for Mitigating Lunar Lander Plume Ejecta.

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Introduction: When a spacecraft lands on the lunar surface, the engine exhaust ejects regolith particles at high velocity [1,2]. It strips away a layer of space-weathered soil from under the lander [3], photometrically alters a region around the lander [4], deposits dust, sand, and gravel in the surrounding locale (and globally for sufficiently large landers), injects a huge pulse of water into the local environment through several transport mechanisms and different resulting distributions of water, modifies the regional atmosphere, deposits other plume chemicals into the surrounding region, sandblasts any hardware within reach [5], and may seriously damage spacecraft in lunar orbit [6]. This can affect the scientific integrity of a mission and the functionality of the spacecraft as well as the surrounding hardware.

Understanding the Physics: The ejection of soil in a high-speed jet of gas in lunar conditions involves several aspects of physics that are not understood. There are too many gas molecules and too many dust grains in a rocket exhaust ejecta event to model using basic mechanics, so the materials must be coarse-grained into continua, but coarse graining without losing the correct physics is not currently possible. For example, the lifting of sand grains from a granular surface is "granular sublimation", a surface process including eddies of gas behind the grains (but in transitionally rarefied flow the turbulence spectrum is truncated), causing grains to roll and bounce on the surface then take flight when gas conditions are adequate. The gas viscosity breaks down in transitionally rarefied conditions so momentum diffusion through the boundary layer is complicated. The roughness length scale in the boundary is a function of how much erosion takes place, which is unpredictable. We need progress in modeling but also empirical data from actual lunar landings to guide the models.

Extent of the Problem: Prior work indicates ejecta from a large lunar lander will occupy a range of velocities including a fraction that exceeds escape velocity. Orbiting spacecraft will be sandblasted as it passes through the ejecta plume, and in low lunar orbit these will be hypervelocity impacts. It is estimated the Lunar Orbital Gateway will sustain 2000 to 10,000 impacts/m^2 [6], although those will not be hypervelocity. Surface assets within a few kilometers in the direct spray may sustain severe sandblasting damage. The extent is more than our "common sense" expects because it is an airless body, so the particles that are accelerated to the highest speeds (dust) are not stopped by an ambient atmosphere as they are on Earth.

Mitigating the Problem: Strategiest to mitigate include building competent landing surfaces, building berms or curtains to block ejecta, landing behind natural terrain features, putting protective covers over sensitive target assets, and timing the landing to miss or reduce impact upon orbital assets. A combination is required since no one can handle every situation. For example, a large lander may be needed for a location where no pre-built pad exists. It is also important to take constant data during lunar landings to monitor the contribution to the lunar "ejectasphere" and to improve modeling. International cooperation will be needed because the ejecta travel globally and beyond.

A Regime for Mitigation: We should seek agreements to minimize sandblasting each others hardware, to allow a certain amount of cumulative sandblasting (since it will be impossible to entirely prevent), and to coordinate landings so assets can be protected by shutting coverings. A regime should include agreement to build a landing pad at any outpost that will be visited more than a few times. The landing pad should be open for international use to comply with the Outer Space Treaty's right-to-inspect. Landers should be designed to move off landing pads to keep them open. Launch and landing events should be openly registered to coordinate measurements and management of the ejectasphere through an international database. Agreements should include a blast size-distance relationship for landing near others' assets.

References: [1] Lane, J. E., Metzger, P.T., Carlson, J.W. *Earth and Space 2010*, 134-142.. [2] Lane, J. E., Metzger, P.T., *Particul. Sci.Tech.*, 30 (2), 196-208. [3] Metzger, P. T., Smith, J., Lane, J.E., *J. Geophys. Res: Planets*, 116, E6. [4] Clegg-Watkins, R. N., *et al.*, *Icarus*, 273, 84-95. [5] Immer, C., *et al.*, *Icarus*, 211 (2), 1089-1102. [6] Metzger, P. T., *Workshop on the Effects of Dust to Human Lunar Exploration*, 2020.

Lunar In-Situ Surface Construction of Infrastructure

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Introduction:

In situ resources offer an opportunity to reduce the amount of items brought from Earth when exploring moons and planets. Utilizing those resources requires energy that comes with a cost. In the case of human missions to Mars, trading surface power for launch mass is beneficial for propellant and consumables required to sustain human pioneering and settlement on the planet's surface. However, In Situ Resource Utilization (ISRU) can mean far more than propellant production and consumables replacement for missions beyond Low Earth Orbit. NASA's Systems Capability Leadership Team (SCLT) for ISRU created a work breakdown structure based on functions identified in roadmaps pertaining to human exploration. That WBS includes Prospecting, Extraction, Processing, Construction, Manufacturing, and Energy. Over the years, NASA has developed some capabilities and technologies for prospecting, extraction, and processing carbon dioxide and water on Mars into propellants and life support consumables. However, that is a small subset of the ISRU needs that are coming to light with NASA's push to return to the Moon for extended periods of time. For instance, astronauts require shielding from Galactic Cosmic Rays and nuclear radiation and protection from the low temperatures and pressures in Space. Surface assets including crew, landers, and ascent modules can be damaged by surface ejecta during landing and launch operations on the Moon and Mars. Creating shielding, berms, and pads requires movement of large volumes and stabilization of regolith in the context of a civil engineering construction project. Because of the multi-disciplinary nature of the aerospace systems needed for human exploration, SCLT on ISRU created an ISRU Construction Integrated Steering Group that combines expertise among several NASA Principal Technologists and Capabilities Leaders for exploring options, assessing opportunities, and developing requirements for construction and manufacturing on the Moon and Mars. NASA's new program to develop Lunar landers for small, mid, and large payload deliveries to the Lunar surface leading to human missions by 2025 spawned an investigation into plume surface interactions caused by the lander during descent and ascent. The trade space to resolve this issue includes regolith stabilization via landing pad construction techniques and lander nozzles characteristics due to vehicle systems design. Some data exists from the Apollo missions but more is required for the missions ahead. The purpose of this paper [1] is to outline an approach for developing requirements that can guide systems designs while taking advantage of flight opportunities in NASA's plans to return to the Moon.

References:

[1] Moses, Robert W. and Mueller, Robert P. (2021) Requirements Development Framework for Lunar In-Situ Surface Construction of Infrastructure. *American Society of Civil Engineers (ASCE), Earth and Space Conference Proceedings*

LISTER: Lunar Instrumentation for Surface Thermal Exploration with Rapidity.

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Abstract: LISTER is a highly compact technology for pneumatic excavation of holes in lunar regolith. The probe can store enough gas to carry instrumentation to a minimum depth of 2 m and up to 3 m.

In penetrating into lunar regolith, the deployment mechanism spools out a boom made of glass fiber and Kapton, in a manner similar to a tape measure. Similar architectures were used for Viking Mars landers' robotic arm and satellite antenna deployment booms. On the way down into the regolith, the boom forms a 2-cm diameter rigid tube. A penetrating cone is attached to the leading end of the boom.

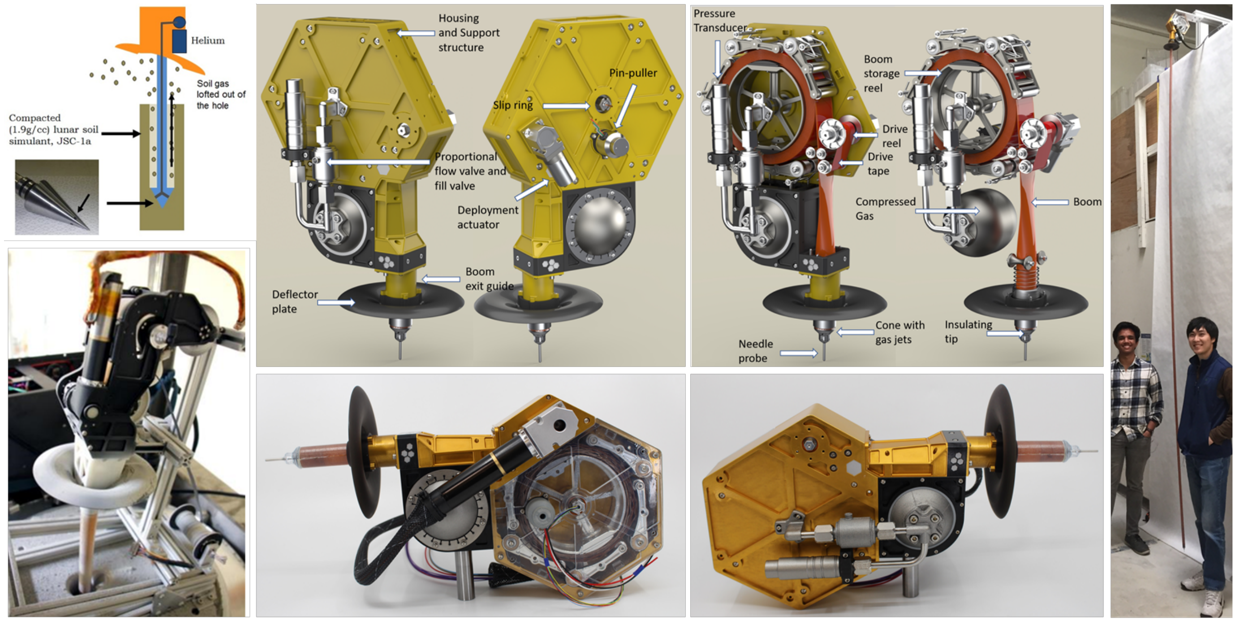

Figure 1. LISTER Compact pneumatic approach for excavating holes in soil.

The pneumatic excavation method provides several benefits for the excavation of loose soil. The high degree of compaction of lunar regolith below ~20 cm [1] results in high force and energy requirements for mechanical excavation. By contrast, pneumatics can take advantage of low particle cohesion to excavate regolith with low forces and minimal gas expenditure [2].

Another advantage offered by this excavation method is rapid deployment. The high velocity of pressurized gas released into vacuum allows for high excavation speeds. LISTER's penetrating cone can reach maximum depth quickly and carry instrumentation with it. This speed of deployment makes it an ideal option for sensing at depth on time-limited missions.

The technology has demonstrated full functionality in 1 g testing under both atmospheric conditions and vacuum. These test cases represent a much more rigorous environment than the low-g vacuum present on the lunar surface.

LISTER spacecraft accommodation: LISTER can be attached to the leg or deck of a lander. It's compact form factor makes it versatile for a wide variety of deployment scenarios.

CLPS Missions: For CLPS, LISTER will be fitted with a heat flow probe. The probe will be used to characterize lunar regolith thermal gradients and thermal conductivity to its max depth between 2 and 3 m.

References: [1] Carrier et al., (2005), The four things you need to know about the geotechnical properties of lunar soil, Lunar Geotechnical Institute. [2] Zacny et al., (2010), Investigating the Efficiency of Pneumatic Transfer of JSC-1A Lunar Regolith Simulant in Vacuum and Lunar Gravity During Parabolic Flights. AIAA Space 2010, AIAA-2010-8702, Anaheim, CA.

Regolith Cohesion Measurement via Induced Electrostatic Lofting. C. T. Pett[1], T. J.G. Leps[2], and C. M. Hartzell[3], [1,2,3]University of Maryland, College Park, Maryland, 20910, United States. (Contact: pett@umd.edu)

Introduction: Electrostatic dust lofting has been hypothesized to occur on airless bodies such as the Moon and asteroids, but in-situ evidence of this phenomenon has yet to be observed. Nonetheless, experiments and numerical models have provided ample insight into the fundamental physics of electrostatic dust mobilization. Prior to lofting, grains are bound tightly to the surface by cohesion, the dominant force for sub-mm particles. However, the magnitude of cohesion in regolith remains poorly constrained. We are developing a technology that will exploit our understanding of electrostatic dust lofting in order to measure cohesion. The same technology may also be useful to induce electrostatic lofting to clear dust from spacecraft surfaces.

We introduce the design of the **E**lectrostatic **Sa**mple **C**ollection and **C**ohesion **Q**uantification (**E-SACCQ**) system, a technology that induces electrostatic dust lofting to measure regolith cohesion. E-SACCQ induces electrostatic lofting of charged regolith grains via a biased attractor plate and simultaneously images their size and trajectory. Since the local gravity is known and the electrostatic force on the regolith grains is controlled by the attractor plate potential, it is possible to solve for the cohesive force on the grains. Furthermore, the ability to induce electrostatic lofting may also provide a new method of dust removal from spacecraft surfaces and for sample collection on rubble pile asteroids.

In this work, we discuss the preliminary design of the instrument. The feedback between the E-SACCQ electrode and the near-surface lunar plasma environment is numerically modeled. Our models predict that solar wind bombardment will be a significant perturbation to the electric field between the surface and the electrode. The system's sensitivity to key design parameters such as attractor plate potential, size, and operating distance above the surface are also assessed. With respect to grain characterization and position tracking, stereo vision is selected as the preferred solution. Additional plasma simulation modeling and experimental demonstration is required to mature this technology.

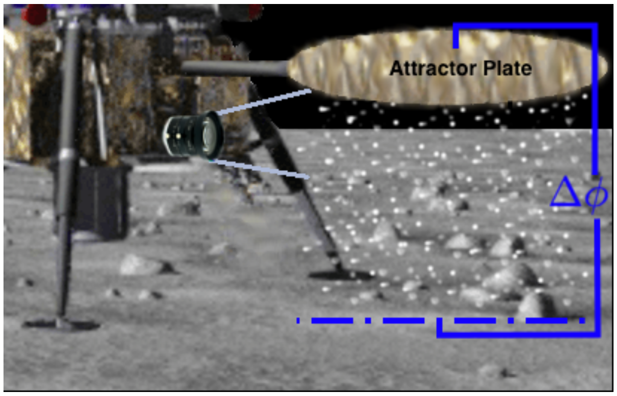

Figure 1: E-SACCQ produces a voltage difference ($\Delta\phi$) with the surface via a biased attractor plate, which induces electrostatic lofting of charged regolith grains. A camera simultaneously images the size and trajectory of the regolith grains. Since the local gravity is known and the electrostatic force on the regolith grains is controlled by the attractor plate potential, it is possible to solve for the cohesive force on the grains. The height of both the attractor plate and the camera is variable. The electric potential of the plate can also be adjusted.

Retractable-Rollable Mast Array (R-ROMA). E. N. Pranckh[1] and T. W. Murphey[2], Opterus Research and Development, Inc.[1,2], 4221 Rolling Gate Rd. Fort Collins, CO 80526[1,2]. (Contact: erik@opterusrd.com, https://www.opterusrd.com)

Introduction: Opterus Research and Development, Inc. is an innovative provider of deployable spacecraft structures. Opterus' expertise and core material technologies; High Strain Composites (HSC), are being applied to solve sustainable Lunar surface power challenges in the regions surrounding the Lunar South Pole.

Innovation & Opportunity: The Retractable-Rollable Mast Array is a vertically deployed and retractable, H-configuration, blanket solar array based on Opterus' collapsible and rollable HSC trussed Collapsible Tubular Mast (T-CTM). The T-CTM is more scalable and capable of supporting higher loads than prior art HSC masts and is the key enabler for the large Lunar surface solar array.

Robust, lightweight, re-deployable solar arrays for lunar surface applications are a topic of great current interest to NASA on its path back to the moon in 2024[1]. Landers, In-Situ Resource Utilization (ISRU) equipment, lunar bases, and rovers will require 10+ kW lightweight solar arrays near the South Pole [1]. These arrays would ideally be repurposed as autonomously deployable and relocatable Lunar surface solar arrays for future missions during the "Sustainment Period" of Lunar South Pole exploration starting in 2028 [2].

R-ROMA is extremely compactible by utilizing a single rollable mast in a H-configuration opposed to two masts deploying a single wing. The mast will use High Strain Composite (HSC) materials that reduce mechanical system part counts by an order of magnitude, increasing dust tolerance. The T-CTM is being developing to handle much greater buckling, torsional, and bending loads than any existing HSC deployable masts developed to date through reinforced HSC laminate designs. With increased structural performance within the mast, the R-ROMA system can be scaled to 10 kW and up to 40 kW.

NASA intends to start delivering payloads to the lunar surface starting in 2024, moving to human exploration and sustainment in 2028 [2]. These missions will be powered by a combination of solar arrays with energy storage, radioisotope power converters, and nuclear fission systems. R-ROMA is envisioned to be the most compact, lightweight, and reliable vertically deployed array for the Lunar surface.

Traction: R-ROMA is currently being developed by leveraging multiple NASA SBIR Phase I and Phase II contracts that are focused on Composite Blanket Element development, T-CTM development, and deployment mechanisms systems design.

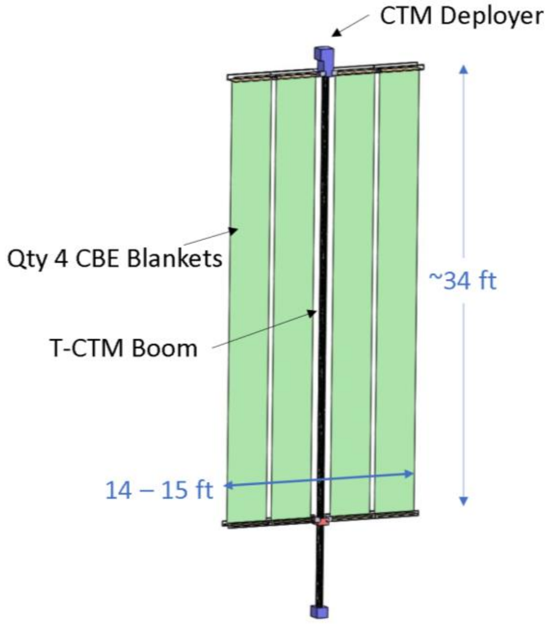

Figure 1 - R-ROMA Deployed

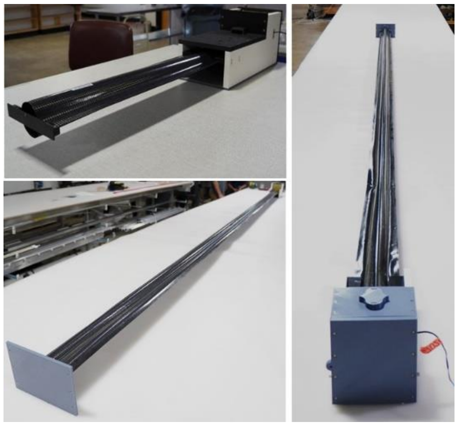

Figure 2 – Subscale T-CTM in EDU Deployer

References:

[1] NASA SBIR/STTR 2020 Program Solicitation. (2020). https://sbir.nasa.gov/solicit/63012/detail?data=ch9

[2] LUNAR VERTICAL SOLAR ARRAY TECHNOLOGY APPENDIX. (2020). https://nspires.nasaprs.com/external/viewrepositorydocument/cmdocumentid=778013/solicitationId={68A7EFE3-1B4F-5AA1-A169-119D97C8DB8F}/viewSolicitationDocument=1/Lunar VSAT_2020 Appendix.pdf

Advanced Planetary Excavator (APEX): A Platform to Measure Excavation Forces and Power. M. P. Proctor[1], [1]NASA Glenn Research Center, Cleveland, Ohio, (Contact: Margaret.P.Proctor@nasa.gov)

Introduction: The Advanced Planetary Excavator (APEX) is a backhoe arm operated by electric linear actuators enclosed in its aluminum housing, which protects components from dust exposure.[1] Installed in the NASA Glenn Excavation Lab (Figure 1), APEX provides a platform to measure the forces and power needed to excavate granular lunar regolith simulants at various compaction levels using different tools, various rake angles, and tool trajectories. Data produced can guide development of efficient digging tools and approaches, and inform mission planners about power requirements and rates of material acquisition. A six-axis load cell between APEX and the tool measures the forces. DC power to APEX is measured with a shunted, in-line power meter. The excavation forces and net power are determined by subtracting tare test results in air from tests in the lunar soil simulant, GRC-3B. Programmed tool paths in the control software provide repeatable trajectories. Measurements using a 21.6-cm wide aluminum bucket with a 25.4-cm wide steel leading edge at 30 degree blade angle have been conducted in the lunar regolith simulant GRC-3B. [2] Example force and net power results are shown in Figures 2 and 3.

APEX: APEX is a four degree of freedom arm with a maximum swing around radius of 2.3 m including load cell and bucket.

Instrumentation: The load cell ranges are 1334 N in x and y and 3892 N in z directions. Uncertainty in force measurements is +/-16.7 N in x and y and +/- 29.2 N in z directions. Torque range is 203.4 N-m. Excavated soil is weighed using a platform scale with a range of 0 to 2224 N and resolution of 0.22 N. A digital power meter and 50 amp shunt are used to measure the total DC power to the APEX. A cone penetrometer is used to assess compaction and uniformity of the prepared soil.

Soil: Lunar soil simulant, GRC-3B, is formulated of silica sand and silt to be similar to GRC-3 [3], but is comprised of different source materials. Inside dimensions of the GRC-3B soil bin are 76-cm W x 183-cm L x 76-cm H. This bin sits on a shaker table used to compact the soil.

References:

[1] Abel, P. B. et al (2019) SRR-PTMSS, 9-2.
[2] Proctor, M. P. (2019) SRR-PTMSS, 9-3.
[3] He, C. et al. (2013) *J. Aerospace Eng.*, 26: 528-534.

Figure 1. Excavation Lab houses the APEX and soil bins inside a dust enclosure.

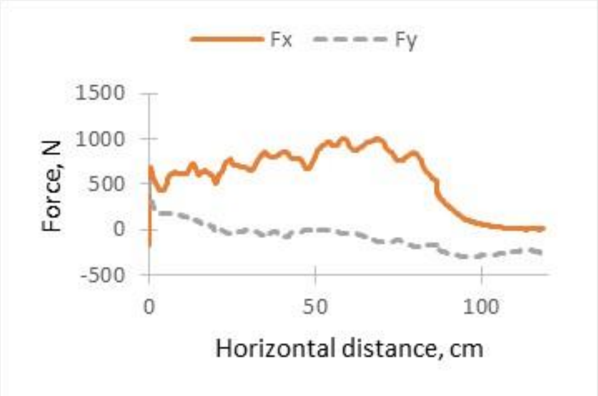

Figure 2. Horizonal and vertical forces, Fx and Fy, on bucket during trajectory in compacted GRC-3B.

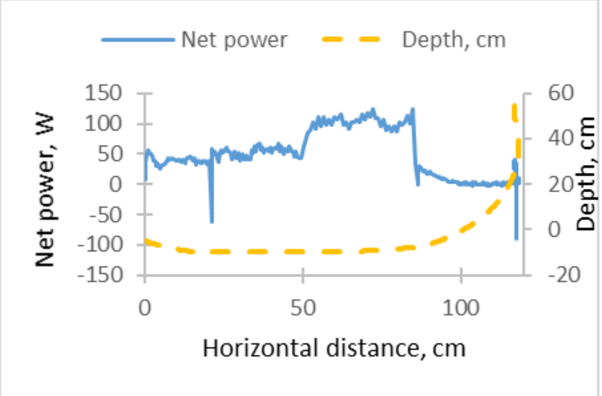

Figure 3. Net power to excavate and depth of bucket tip during trajectory in compacted GRC-3B.

The CubeRover for Lunar Mobility as a Service.

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Introduction: The CubeRover is a first of its kind ultra-light, modular, and scalable commercial rover. Combined with commercial payload services available in CLPS, it offers a low-cost onramp to the Moon for payload developers globally. CubeRovers (Figure 1) utilize a methodology akin to CubeSats in that they support diverse instrument packages in a standard form factor. CubeRovers leverage the internationally recognized CubeSat sizing method to define the payload volume and carrying capacity, where a 10 cm X 10 cm X 10 cm volume that supports 1 kg of payload is called a unit or "U." Accordingly, the 2U CubeRover has a payload volume of 20 cm X 10 cm X 10 cm and supports 2 kg of payload. The 4U and 6U CubeRovers grow in size and carrying capacity with their respective U designation. Larger versions of the rover utilize the same structural, power, thermal, avionics, and software systems to minimize re-engineering costs. CubeRovers are highly customizable to meet the needs of precise payload demands. An overview of payload services that each CubeRover provides is shown in Table 1 and is detailed in the CubeRover Payload User's Guide on Astrobotic's website.

Robust Lunar Applications: CubeRovers offer groundbreaking new modes of operation for rover-based science and exploration. For instance, multi-agent autonomy can be incorporated into CubeRovers to conduct swarm operations and improve the distance traveled on planetary surfaces, the speed-made-good, and co-localized accuracy of collected data. One rover could be equipped with a neutron detector or spectrometer while another is equipped with ground penetrating radar. Using multi-agent autonomy, both rovers could collaborate autonomously to map the surface and subsurface of a lunar region. An alternative configuration of the rover could integrate a robotic arm, to sample regolith or interact with deployed payloads

Figure 1: Astrobotic's CubeRover.

Technology Advanced Through Investment: CubeRovers leverage significant prior NASA investment. By investing more than $4M and three years of resources in the CubeRover technology, NASA has unlocked the potential of this platform so that it can support the collection of high value science data on the lunar surface for years to come.

Price: Astrobotic offers its mobility as a service price of $4.5M per kilogram of mobile payload delivered on the lunar surface, which includes end-to-end delivery of each payload on Astrobotic's Peregrine or Griffin landers. This firm fixed price service includes integration of the payload on CubeRover, integration of CubeRover on Astrobotic's landers, selection of launch opportunities, provision of end-to-end services including operations associated with the launch vehicle, launch site, spacecraft, lander, mission design and analysis, ground systems, and payload support.

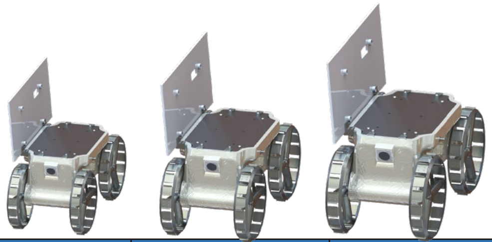

Table 1: CubeRover services.

	2U	4U	6U
Rover Mass	3 – 4 kg	6 – 8 kg	10 – 12 kg
Payload Capacity	Up to 2 kg	Up to 4 kg	Up to 6 kg
Internal Payload Max Dimensions	20 x 10 x 10 cm	20 X 20 X 10 cm	30 X 20 X 10 cm
Payload Nominal Power Services	0.5 W per kilogram continuous, 10 W peak		
Payload Power Interface	28 Vdc		
Payload Thermal Environment	-20C to 60C		
Payload Wired Interface	RS-422		
Payload Comms Services	10 kbps per kilogram		
Payload Wireless Standard	WLAN 802.11n		
Payload Data Storage	32 Gb +		

Radiation Tolerant High-Voltage, High-Power Diamond Electronics. P. Quayle,[1] K. Evans,[1] M. Muehle[2] and T. Grotjohn[3], [1]Great Lakes Crystal Technologies, 104 Dawn Ave., East Lansing, MI, [2]Fraunhofer USA Center for Coatings and Diamond Technologies, 1449 Engineering Research Ct, East Lansing, MI 48824, [3]Michigan State University, 220 Trowbridge Rd., East Lansing, MI 48824 (Contact: quayle@glcrystal.com)

Introduction: It is well known that the harsh space radiation environment presents many challenges to the function of electronics outside the protection of Earth's magnetic field. Continual advances in space exploration and habitation require electronics capable of withstanding both the long-term effects of radiation and probabilistic catastrophic failure events caused by high energy, heavy ions. Great Lakes Crystal Technologies, in partnership with Fraunhofer CCD, is pursuing a potential solution to the problem through the development of radiation tolerant diamond electronics. The research underway capitalizes on decades of technology development that has emerged from the collaborative efforts of Michigan State University and Fraunhofer CCD. Diamond is superior to other semiconductors in terms of radiation tolerance owing to its strong C-C covalent bonds and very high thermal conductivity. Additionally, diamond has a larger energy loss per electron-hole pair generated than other semiconductors, so fewer e-h pairs are generated per unit of energy deposited by the heavy ions. In this presentation, we will describe our efforts towards the development of diamond Schottky diodes and pn junction diodes.

Strategies for Lunar in Situ Resource Utilization: Adaptive Material Extrusion-based Additive Manufacturing using Lunar Regolith.

M. H. Rahman[1], A. Hayes[2], M. S. Shafae[1], K. Muralidharan[2], and D. A. Loy[2,3], [1]Department of Systems and Industrial Engineering, [2]Department of Materials Science and Engineering, [3]Department of Chemistry and Biochemistry, The University of Arizona, Tucson, AZ 85721, USA. (Contact: shafae1@arizona.edu)

Introduction: Additive manufacturing provides new pathways for the rapid production and replacement of engineering parts, components, devices, and structural elements in remote environments such as the lunar terrain. When combined with strategic in-situ utilization of indigenous resources, additive manufacturing can greatly reduce the complexity of the material supply chain and resolve logistical problems involved with manufacturing and repair needs in remote environments and extreme conditions. In this regard, we have developed a new material extrusion-based additive manufacturing system that enables the optimal use of lunar regolith constituents to fabricate on-demand parts and components; providing straightforward routes for repair and refurbishment. The unique and distinctive aspect of the developed methodology is the minimal reliance on non-indigenous material-feedstock and the portability of the manufacturing unit.

Materials and Methods: Several promising additive technologies including laser powder bed fusion and selective laser sintering are under investigation for utilizing in-situ resources [1]. Current approaches have strict requirements for material collection and processing, equipment, and process control. Keeping these constraints in mind, and noting the availability of water-ice at the Moon's poles, we have developed a hydrogel-based material formulation using Pluronic hydrogel and lunar regolith simulants that enables higher material utilization and greatly reduces material pre-processing steps (lunar regolith can be used in its unrefined state, only requiring sieving), while simultaneously allowing the printing of dense components [2]. Next, for developing and optimizing a printing process that is adaptable and scalable to remote manufacturing, we adopted the robocasting technique due to its rapid extrusion capability, ease of operation, and the moderate requirement of operators' training and maintenance. We modified a commercially available printer and used it for additive manufacturing of structures and parts. To identify the processability region of our newly developed material, we conducted several pilot experiments. After identifying the printability range for the system, we performed a full-factorial design of experiments to evaluate the effects of critical printing parameters, such as printing speed and extrusion rate, on the print quality and shape retention, in the printed parts. An illustration of the extrusion process is given in Figure 1.

Results and Discussion: The developed regolith-hydrogel formulation was optimized to demonstrate tunable thixotropic properties that are required for on-demand remote manufacturing. Our results advocate that with access to water-ice - there is evidence of water on the moon as well – production and/or repairing of parts will only require 10 wt.% of material to be carried into the remote environment. Further enhancement of the mechanical and structural robustness of the printed parts can be achieved via sintering. Importantly, we have successfully printed our material using an extrusion-based process, for which, we also determined the process feasibility window to ensure stable deposition and shape retention of the material, reducing on-site decision making.

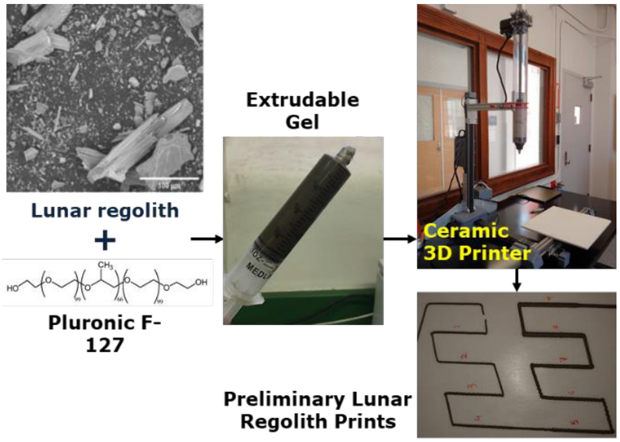

Figure 1: Proposed System Process Flow

Summary: We have developed a scalable, and energy and cost-efficient in-situ resource utilization system capable of processing inhomogeneous lunar regolith into useful parts and components. The result of this work can broaden the potential use of native minerals in resource-limited far off environments on Earth and in future Lunar exploration.

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Mission to Planet Earth: Alaska Villages Rescue. Shove, Christopher, Executive Director, Xtreme Habitats Institute, 7200 Wisconsin Avenue, Suite 500, Bethesda, Maryland cshove@xtremehabitats.org

Introduction: Xtreme Habitats Institute ("XHI"), a non-profit corporation, was established to facilitate the research, design, development, test and implementation of extreme environment villages (XHV) to help overcome the difficulties of living and working in isolated and extreme environments, such as the following.

- Alaska's Arctic Region, where commercial, scientific and national security activity is expected to increase, and where existing 86% of Alaskan Native villages are affected by extreme temperatures, thawing permafrost, flooding, and coastal or riverbank erosion. At least 31 of these villages may have to be relocated in the next 5-10 years.

- Other difficult environments around the world, e.g., polar regions, arid deserts, isolated remote locations, etc.
- Future outposts on the Moon and Mars.

Scope of Work: XHI will take a systems-level approach to the design and development of these unique XHV habitats, incorporating local knowledge, international best practices and NASA technology transfer, along with urban planning principles and design criteria.
XHI seeks input on appropriate technologies from International Space Station, proposed Artemis 3 lunar base camp, and Subject Matter Experts for short-term consulting to prepare technical reports on appropriate technologies.

The XHV will consist of connected structures optimally designed for living and working in extreme environments. The XHV habitats will include the following.

- Connected structures (houses, workspaces, etc.) for high-quality living and working (constructed using advanced technologies such as 3D printing with in-situ materials).
- Local sources of sustainable energy (e.g., hydrogen, wind, geothermal, solar, etc.).
- Self-sufficient food production (e.g., hydroponics and aquaculture).
- Clean water and air production and recycling and closed loop systems.
- Infrastructure for utilities, solid waste management, transportation, communications, etc.
- Facilities for programs in education, recreation and entertainment, public health and social space.
- Framework for a local support economy.
- Ecological sustainability.

Best technologies are selected according to a benefits/costs ratio and use of in-situ resources.

References:

Mendell, Wendell (Ed.) (1984) Lunar Bases and Space Activities of the 21st Century. Lunar and Planetary Institute.

A DEEP SPACE RATED COMMUNICATIONS HUB FOR LUNAR EXPLROATION. M. Sommers[1], L. D. May[2], and C. W. Nie[3], [1]Lockheed Martin (marc.sommers@lmco.com), 12257 S Wadsworth Blvd, Littleton, CO 80127. [2]Lockheed Martin (lisa.d.may@lmco.com), [3]Lockheed Martin (christopher.w.nie@lmco.com).

Introduction: Lockheed Martin (LM) proposes an Orion heritage WIFI unit to enable intercommunication between distributed payloads on the lunar surface. This system is based on LM's extensive deep space spacecraft heritage in developing sophisticated technologies and capabilities with proven processes. Lunar landers will carry various science packages, sensors deployed locally, and small rovers to explore around the landing site. To facilitate the control and relay of data from each of these assets, use of a local area network or WiFi, centered around the lander as a hub provides various advantages. Use of a wireless interface simplifies integration with any given commercial lander by providing an untethered interface for a science package, requiring that the science experiment connect only to the lander's local area network to receive commands and relay data via the lander back to Earth.

System Pedigree: The NASA/Lockheed Martin-developed video architecture for the Orion spacecraft uses a camera controller that provides wireless connectivity using both the IEEE 802.11n and 802.11ad standards to communicate with and stream data from multiple video cameras. The 802.11n standard is used in the 5 GHz band and can communicate with four cameras at data rates up to 52 Mbps. The data rate varies dynamically, dependent on the signal environment and received threshold power in the link. The 802.11ad capability is implemented on a 60 GHz link, with a data rate of up to 1.1 Gbps.

The Camera Controller acts as a wireless hub providing a WiFi network to connect the various video cameras to the spacecraft's command and data handling (C&DH) subsystem. The controller contains a commercial single-board computer (SBC) with solid-state storage, which allows the video to be stored if necessary and retrieved later for downlink to the ground. In addition to the WiFi connectivity provided, the controller allows for additional cameras to be connected via a USB3 hardline.

Next Generation Evolution: We propose to leverage the Orion Camera Controller to develop a next-generation unit that evolves the controller into a central WiFi hub that can be used on any platform. The current WiFi radio card would be replaced with a WiFi 6 (802.11ax) chipset implemented onto a daughter card that is integrated into the unit. This would provide transfer speeds in excess of multiple Gbps and with a range of approximately 350 feet. This approach would allow the daughter card to be updated as needed for parts obsolescence or as the state-of-the-art is advanced by the commercial sector. A modular design approach for the daughter card would leverage COTS components and next-generation industry standard connector technologies to speed development and support future upgrades.

Lunar Mining Base Development and Operations: The Case for Multirobot Systems. J. Thangavelautham[1] and Y. Xu[1], [1]Space and Terrestrial Robotic Exploration (SpaceTREx) Laboratory, Univ. of Arizona, 1130 N Mountain Ave., Tucson, Az, 85721. (jekan@arizona.edu)

Introduction: The development of a space economy will require identifying and mining critical resources that will minimize cost and energy usage. The Moon is one potential candidate. It is rich in iron, titanium, and silicon. Water is thought to exist in large supplies in the Permanently Shadowed Regions (PSRs) of the lunar poles. Based on these findings, we plan on developing an energy model to determine the feasibility of site-preparation and developing a mining base on the Moon. This mining base mines and exports water, titanium, steel, and aluminum.

Mining Base Model: Our design for a mining base utilize renewable energy sources, namely photovoltaics and solar-thermal concentrators, to provide power to construct the base, keep it operational, and export water and other resources using a Mass Driver. However, the site where large quantities of water are present lack sunlight, and hence the water needs to be transported from the southern region to a base located at mid-latitude. Using the energy model developed, we will determine the energy per Earth-day to export 100 tons each of water, titanium, aluminum, and low-grade steel into Lunar escape velocity.

Challenges and the Need for Robotics: Our study of water and metal mining on the Moon found the key to keeping the mining base efficient is to make it robotic. Mineral deposits are known to be dispersed over large tracts of the lunar surface. The mineral ore deposits are likely diffuse, and it will require mining at large scales, through open-pit mining to make the whole effort feasible. The inhospitable conditions on the Moon due to the low-gravity, lack of atmosphere, high-temperature variations, solar and cosmic radiation, and micrometeorites all suggest the need for robotic systems to perform these tasks. Robots are ideally suited for open pit mining on the Moon as its a dull, dirty, and dangerous task. We modeled the excavation robots using the Balovnev model [1]. Excavation robots considered include front-loaders, bucket-wheels, and bucket-wheel variants such as RASSOR [2]. One of the challenges is to scale up productivity with an ever-increasing number of robots. Another challenge is the low-gravity of the Moon that reduces traction on ground vehicles.

Multirobot Solution: Our work in this field showed that fleets of autonomous decentralized robots have an optimal operating density. Too few robots' result in insufficient labor, while too many robots cause *antagonism,* where the robots undo each other's work and are stuck in gridlock (Figure 1) [4]. These robot controllers were evolved using a form of evolvable neural networks [3]. Our findings show that individual robots can have sensory and actuator limitations, yet working together as a group, we can obtain robust team performance. Our earlier work found that the best of these evolvable robot controllers are *human-competitive* [4].

Optimized Configurations: It is possible to increase robot densities further than the approaches stated earlier and see improved performance, but utilizing highly structured cooperative behavior such as bucket brigades. Another is the aggregation of robots into a large robot collective, much like an Ancient Roman *Tortoise Formation*. The aggregation behavior results in near-optimal performance, in which a larger robot entity that is composed of x robots operate in parallel and results in T/x time to complete the task where T is the time needed by one robot to complete the task.

Conclusions: Teams of robots would be used to construct the entire base using locally available resources and fully operate the base. We first consider export of 100 tons each of water, low-grade steel, aluminum, and titanium. Our results show constructing the base using 3D printing methods, and local resources in addition to operation using robot teams would decrease energy needs for construction by 23-folds [5]. We further analyze the impact on increasing export by a further 10-folds and find that robotic-3D printing solution results in linear growth in energy needs for construction while conventional construction methods and the use of human teams would see an exponential increase in energy needs.

References:

[1] V. Balovnev, *New Methods for Calculating Resistance to Cutting of Soil*, Amerind Publishing [2] R. Mueller et al., "Regolith Advanced Surface Systems Operations Robot," IEEE Aerospace Conference, 2013. [3] J. Thangavelautham, G.M.T. D'Eleuterio, G.M.T. (2012) "Tackling Learning Intractability Through Topological Organization and Regulation of Cortical Networks," *IEEE Trans. Neural Netw. Learn.* [4] J. Thangavelautham, et al. "Autonomous Multirobot Excavation for Lunar Applications," *Robotica* , pp. 1-33, 2017. [5] J. Thangavelautham, "Autonomous Robot Teams for Lunar Mining Base Construction and Operation," *IEEE Aerospace Conference 2020*, Big Sky, MT, 2020.

Design and Testing of a Robot to Deploy a Super-Conducting Power and Communication Cable down into a Lunar PSR. P.J. van Susante[1] and M.C. Guadagno[2], [1]Michigan Technological University, 1400 Townsend Dr., MEEM815, Houghton, MI 49931, [2]Michigan Technological University, 1400 Townsend Dr., MEEM815, Houghton, MI 49931. (Contact: pjvansus@mtu.edu)

Introduction: NASA is interested in accessing and processing potential ice resources in the lunar Permanently Shaded Regions (PSRs).The PSRs have very cold temperatures due to no sunlight and no direct line of sight to the landing location. Ground operations down in the PSR have challenging power and communication constraints. One possible solution to minimize battery size and communication constraints is to deploy a superconducting power and communication cable down into the PSRs and be a power charge and communication relay point in the PSR. Power would be-generated at the landing site and transferred via the cable down into the PSR. Other ground vehicles can then dock and recharge as well as have continuous communication via the relay station which then would allow much less constraints on the communication and power systems of the ground systems operating in the PSRs.

NASA BIG Idea Competition: A team of students from Michigan Technological University (MTU) decided to submit a proposal to The 2020 BIG IDEA Challenge: Capabilities to study dark regions on the Moon. Three topics 1) Exploration of PSRs in lunar polar regions, 2) Technologies to support lunar in-situ resource utilization (ISRU) in a PSR 3) Capabilities to explore and operate in PSRs. Our proposal T-REX (Tethered - permanently shaded Region EXplorer) was chosen as 1 of the 8 awardees. T-REX will deploy a lightweight, superconducting cable for power and communicat ions into a permanently shadowed region. It will be unspooled by a two-wheeled rover that traverses down the slope of the crater. After reaching its final destination, the rover becomes an electrical recharging hub and a communications relay for other robots operating in the dark region. This technology leverages the ultra-cold temperatures of the Moon's polar shadows, enabling the use of superconducting materials without active cooling systems.to deploy a superconducting cable down into the PSR. The goal of the competition is to bring the technology to TRL-6 and test it in relevant environment.

Design Phase: The T-REX rover has been designed and built in two phases; a mark 1 rover for atmospheric testing and a mark 2 rover for testing in MTU's Planetary Surface Technology Development Lab's (PSTDL) dusty thermal vacuum chamber (DTVAC).

Progress: To do the testing in the relevant environment, A large sandbox (16ftx6ftx1ft) was built and filled with a home-made simulant (MTU-LHT-1A) consisting of a specific mixture of crushed basaltic scoria and pure anorthite (Greenspar 90 and Greenspar 250). The mixture was optimized to represent lunar highland regolith particle size distribution and mineral composition. The Mark-1 T-REX is currently being tested in the sandbox (see figure1). Further ongoing testing includes traversing slopes and obstacles as well as cable deployment, power and communication transfer and docking.

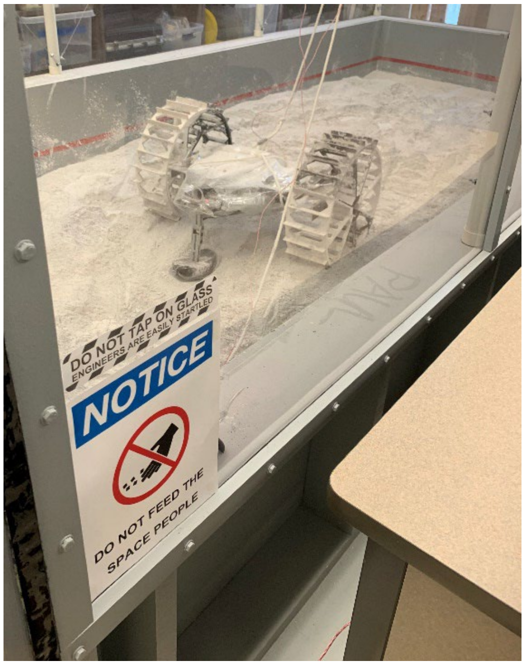

Figure 1: T-REX test in regolith simulant bin

Future Tests: The mark 2 rover is designed and is being built to start testing in the 50 inch x 50 inch x 70 inch DTVAC with the superconducting cable deployment at -196°C and overall thermal systems testing as well as driving and docking in the DTVAC. When fully tested, the approximately 30 kg rover can deploy several kilometer of superconducting cable down into a PSR.

Overview of Nuclear Power Capabilities and Considerations for Applications on the Lunar Surface

Paolo Venneri, p.venneri@usnc-tech.com

Nuclear power systems are an enabling technology for the development of human activities on the lunar surface and beyond. Characterized by the ability to provide kW and MW scales of power in compact form factors coupled with relative insensitivity to the environment, nuclear power systems are game-changing in their potential. Importantly, nuclear systems provide a solution for power and heat during the lunar night and in permanently shadowed regions.

Key to the successful implementation of space nuclear systems is understanding their design drivers, the current state-of-the-art for nuclear reactor technology, and the changing regulatory and policy environment surrounding their implementation. This talk presents an overview of these topics to better inform the community at large on the applicability of space nuclear power systems to the lunar surface.

The design space for space nuclear systems traditionally driven by the need to minimize the mass per unit power output (alpha) of the system. This has led to optimization for metal fueled HEU reactor systems that are compact and able to fit in a mass budget of less than 3 metric tons. However, as we come closer to implementation and the lunar infrastructure develops, it is becoming increasingly clear that other design drivers are gaining importance that require different design choices. The needs of the emerging lunar infrastructure open the design space from mass optimization to include other factors that will lead to a sustainable and commercially attractive presence on the moon. Examples of emerging design drivers include scalability of technology to 100s of kW and MW power levels, inherent barriers to nuclear proliferation, inherent accident tolerance, fission product retention, overlap with terrestrial nuclear power system, and affordability.

Recent technology advancements for space nuclear systems include overlap in developments of nuclear fuel and materials technology, high-temperature deployable radiators, compact power conversion systems, and microgrid integration. By taking these into account, new systems can be envisioned that are able to meet growing demands and address competing community needs and requirements.

A key factor in the current enabling of space nuclear systems is the recent "Presidential Memorandum on the Launch of Spacecraft Containing Space Nuclear Systems." In this memorandum, the executive branch makes clear distinctions between radioisotope and fission power and prolusion systems as well as systems using Highly Enriched Uranium (HEU) and High Assay Low Enriched Uranium (HALEU). By introducing a tiered system, the memorandum opens the pathway for the launch of nuclear systems that do not require presidential authorization and opens the possibility for commercial launches of commercial systems.

A New Technique for Lunar Dust Mitigation Utilizing an Electron Beam.

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Introduction: Dust particles stirred up by human/robotic activities and/or naturally lofted on the lunar surface are likely to stick to every surface, and the fact that they have excess electrical charge due to natural plasma and/or triboelectric effects makes them to be even stickier and harder to be removed. Dust hazards have been recognized during the Apollo missions [1], which include damage to spacesuits due to the abrasiveness of lunar dust, degradation of thermal radiators, reduction of return efficiencies of the retroreflectors, interference with hatch seals and Extravehicular Activity (EVA) systems, and the health risks of inhalation by astronauts.

Over the past decades, several dust mitigation technologies have been studied and developed [1]. These technologies can be divided into four categories: fluidal methods (e.g., compressed gases), mechanical methods (e.g., brushing), electrodynamic methods (e.g., Electrodynamics Dust Shield) and passive methods (e.g., anti-adhesion surface modifications).

Here we present a new technique utilizing an electron beam to charge and shed dust particles off of surfaces as a result of electrostatic replusive forces [2]. This method aims to clean fine-sized lunar dust particles (<25 µm in diameter) that have been recognized as a challenge in dust mitigation.

Experiment and Results: This new technique is developed from recent scientific studies on electrostatic dust lofting [3]. It shows that the emission and absorption of secondary electrons and/or photoelectrons inside microcavities formed between dust particles can cause a buildup of substantial negative charges on the surrounding particles, such that the subsequent repulsive forces between these particles are large enough to release them from the surface.

The experiment is performed in a vacuum chaber, as shown in Fig. 1. Lunar simulants (JSC-1A, <25 µm) are deposited on a sample surface attached to a plate. The dust sample is exposed to an electron beam emitted from a hot filament. Figure 2 shows dust particles jumping off a glass surface and its before & after pictures of dust being removed.

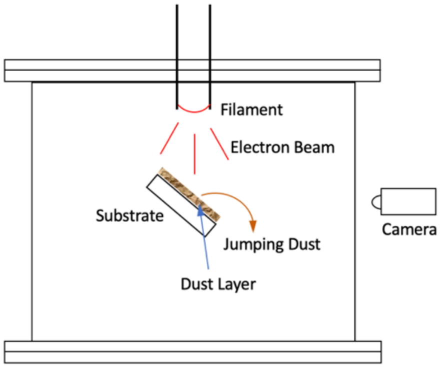

Fig. 1 Schematic of the experimental setup

The cleaning performance is tested against the electron beam energy and current density, the surface material (spacesuit sample and glass), as well as thickness of the initial dust layer. It is shown that the overall cleanliness can reach 75-85% on the timescale of ~100 seconds with the optimized electron beam parameters (~230 eV and minimum current density between 1.5 and 3 µA/cm^2).

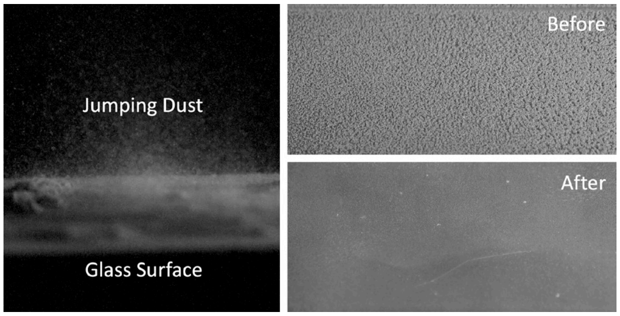

Fig. 2 Left: Dust jumping off a glass surface due to exposure to an electron beam; Right: Images of the glass surface before and after the beam exposure.

Conclusion: We demonstrated a new technique using an electron beam to charge and shed dust off of various surfaces for future lunar surface exploration. This technique showed promising cleaning efficacy to clean fine-sized dust particles (<25 µm). Future work will be focused on removal of the last layer of dust particles to further improve the cleaing rate.

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Understanding the Impact of High-Velocity Dust Due to Lunar Landings. M.M. Wittal[1], Bruce Vu[1] James Mantovani[1], P.T. Metzger[2], and D.H. Fontes[2], [1]Granular Mechanics and Regolith Operations Laboratory NASA Kennedy Space Center, 32899, [2]University of Central Florida Planetary Sciences Group, 4111 Libra Dr. PSB 430, Orlando FL, 32816 (DurContact: mmwittal@nasa.gov)

Introduction: Evidence from earlier landings by Surveyor and Apollo have provided ample evidence regarding the dangers of high-velocity ejecta [1,2,3]. These dangers include the generation of dust that settle on equipment, posing a hazard to equipment following landing, the sandblasting of objects near the landing site, and the spread of high-velocity dust over the entire lunar surface and in lunar orbit that may remain for long periods of time. Recent work has provided valuable insight into the behavior and nature of the dust as a function of lander size, but further work is needed to gain a better understanding of the initial trajectories of this high- velocity dust.

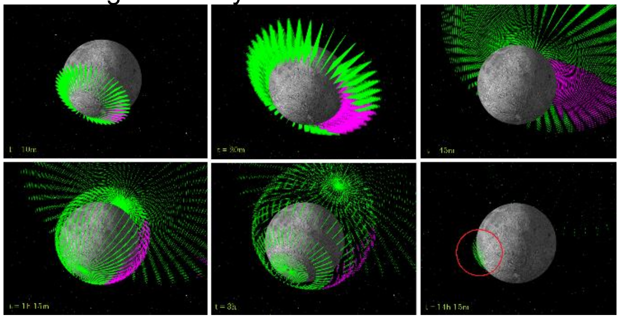

Figure 1. A numerical simulation of high-velocity dust in the lunar environment. Purple particles are in shadow.

High-Velocity Dust: This work provides a basis for understanding the impact of high-velocity dust near the landing site, across the surface of the mon, and in lunar orbit. By starting with a well-constrained set of initial conditions and considering environmental factors such as electromagnetic charge and multi-body dynamics, a broad picture of the consequences of dust due to lunar landing plumes can be assembled [1]. Initial conditions are determined using computational fluid dynamic simulations while the impacts of dust at the higher velocities are traced using numerical integration.

References:

[1] Wittal, M.M. et al. (2020) *AIAA 20-511.* [2] Wittal M.M. and Powers R.J. (2019) *AIAA 19-616.* [3] Lane, J.E. and Metzger, P.T. (2015) *Faculty Bibliography 2010s* 6646.

PVEx: Planetary Volatiles Extractor. K. Zacny, P. Chu, V. Vendiola, S. Indyk, Honeybee Robotics, 2408 Lincoln Blvd., Altadena, CA 91001. (zacny@honeybeerobotics.com)

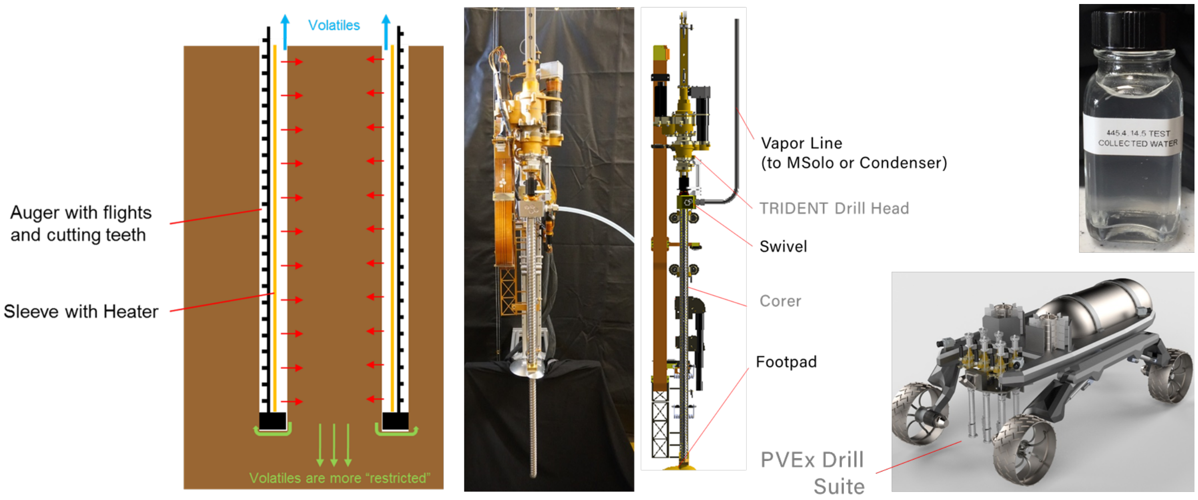

Figure 1. PVEx Volatile Extraction Drill System Overview.

Introduction: Planetary Volatiles Extractor (PVEx) is a volatiles delivery system that can be used for both prospecting missions (provide volatiles to Gas Chromatograph Mass Spectrometer - GC/MS) as well as mining missions (capture volatiles in cold trap for processing). The heart of the PVEx is a coring auger with internal. The coring auger is driven into the ground by a rotary-percussive drill, TRIDENT, currently under development for VIPER missions.

To arrive at the PVEx design, we investigated many other approaches to extracting of volatiles from planetary regolith [1]. These investigations were test heavy. Numerous prototypes were developed and then tested under relevant conditions of frozen regolith doped with various water wt.% and in vacuum. The tests included NU-LHT-2M lunar highland simulant and JSC-1a lunar mare simulants. Water wt.% was varied from 2% all the way to full saturation of around 12%.

During testing, it was found that heating of regolith is a significantly easier step than capturing of sublimed volatiles [2]. In many architectures the capture efficiency was zero – that is, all volatiles that have been sublimed, were lost to "space" (i.e. interior of a vacuum chamber), while no molecules made their way into a cold trap. The PVEx architecture works well because the coring auger seals the path the volatiles take and prevents this escape.

The PVEx coring auger is driven to depth by a rotary-percussive drill. Once it has progressed to a target depth and forms the regolith core, the heaters lined up on the inside the coring auger are turned on. The conductive/radiative heat warms up the core and liberates volatiles. Volatiles then flow up the coring auger, through the swivel and either directly into GCMS or into a cold trap where they re-condense. The benefit of an intermediate cold trap is that the volatiles flow could be metered out to the GCMS. Using this method of volatile collection ensures that far less volatiles are lost through sublimation to the vacuum of space.

PVEx is the only ISRU system that has demonstrated the end-to-end steps required to deliver volatiles to a cold-trap: penetrating icy-regolith, sublimating volatiles, re-capture of volatiles on a cold finger. It has a significant potential to be both a prospecting tool as well as a mining tool – the differences are in the size of the coring auger.

The modularity of the PVEx means that it can be deployed in a suite of drills to increase collection capacity. The end-to-end extraction of volatiles provides a huge advantage over other ISRU systems that require significant infrastructure for operation.

References: [1] Vendiola et al., (2018), Testing of the Planetary Volatiles Extractor (PVEx), ASCE Earth and Space Conference, Cleveland, OH. [2] Zacny et al., (2016), Planetary Volatiles Extractor (PVEx) for In Situ Resource Utilization (ISRU), ASCE Earth and Space Conference, Orlando, FL.

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