Lunar
Surface
Innovation
CONSORTIUM

FALL MEETING PROGRAM

OCTOBER 10-11, 2023

JOHNS HOPKINS
APPLIED PHYSICS LABORATORY

WELCOME

Thank you for joining us for the LSIC 2023 Fall Meeting!

We would like to thank the Community College of Allegheny County (CCAC) for hosting this meeting and NASA, Keystone Space Collaborative, Astrobotic, and Moonshot Museum for helping coordinate this event and provide subject-matter experts who will present throughout the meeting. We are extremely grateful to the many speakers, moderators, panelists, and supporters who are participating to make this event a success. We appreciate all our attendees. We look forward to spending these two days with you. For additional details and the full program, please visit the event page here:

https://lsic.jhuapl.edu/FallMeeting2023

SLIDO INFORMATION (Q&A TOOL)

To make sure virtual and in-person attendees have the same access to the Q&A during the event, we will be using a tool called Slido. You can use either your phone or your computer to submit questions as well as to upvote questions other participants have submitted. Use the QR code or URL and event code below to participate!

http://sli.do
Event Code: #2023LSICFall

WI-FI

Attendees are welcome to utilize the CCAC-Guest Wi-Fi network during the event. Instructions for how to connect to Wi-Fi are listed below.

Windows

1. On the taskbar, click the Wi-Fi icon
2. Click on CCAC-Guest from the available Wi-Fi list
3. Click the Connect button
4. A browser page will open
5. Click the Create a Guest Account link
6. Enter your information
7. Click the Create Account button
8. You will receive a text message and/or email with login information
9. Enter your guest username and password from the email/text message
10. Accept the terms
11. Click the Sign On button
12. You will be taken to the CCAC Homepage once connected

Mac

1. On the Mac menu bar, click the Wi-Fi icon
2. If CCAC-Guest Wi-Fi is not showing, click Other Networks
3. Select CCAC-Guest Wi-Fi
4. A browser page will open
5. Click the Create a Guest Account button
6. Enter your information
7. Click the Create Account button
8. You will receive a text message and/or email with login information
9. Enter your guest username and password from the email/text message
10. Accept the terms
11. Click the Sign On button
12. You will be taken to the CCAC Homepage once connected, click Done

WI-FI, CONTINUED

iPhone/iPad

1. Open the Settings App
2. Go to Wi-Fi
3. Choose CCAC-Guest from the network list
4. Choose the Create a Guest Account link
5. Enter your contact information
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7. You will receive a text message and email with sign-up information
8. Enter the given username and password
9. Agree to the terms and conditions
10. Tap the Sign On button

Android

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2. Tap on Connections
3. Go to Wi-Fi
4. Choose CCAC-Guest from the network list
5. Choose the Create a Guest Account link
6. Enter your contact information
7. Tap the Create Account button
8. You will receive a text message and email with sign-up information
9. Enter the given username and password
10. Agree to the terms and conditions
11. Tap the Sign On button

Additional Wi-Fi connection instructions can be found here:
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AGENDA

DAY 1

All times are Eastern Daylight Time.

TIME	EVENT	SPEAKERS(S) OR DETAILS
8:30 AM	Coffee, Networking & Registration	
9:30 AM	Welcome	**Jamie Porter**, LSIC Director, JHU/APL **Quintin Bullock**, President, Community College of Allegheny County **Hon. Summer Lee**, U.S. House of Representatives **Cathleen Richards**, Interim Executive Director, Moonshot Museum **Justine Kasznica**, Keystone Space Collaborative
10:20 AM	NASA Space Tech Keynote	**Prasun Desai**, Associate Administrator (Acting), NASA STMD
10:50 AM	Break (10 minutes)	
11:00 AM	NASA Announcement	**Introduction -** **Niki Werkheiser**, Director of Technology Maturation, NASA STMD **Walt Engelund**, Deputy Associate Administrator for Programs, NASA STMD
11:35 AM	LSII & LSIC - A Look Back	**Rachel Klima**, Former LSIC Director **Jamie Porter**, LSIC Director
12:00 PM	**Lunch Break** (90 minutes) and Moonshot/Astrobotic Guided Tour, Caterpillar Remote Mission Control Stations, Science and Technology Policy Institute (STPI) Roundtable Discussion	
1:30 PM	**Panel**: Minimum Viable & Resilient Infrastructure **Moderator**: Jibu Abraham, JHU/APL	**Tipping Points Intro -** **Niki Werkheiser**, Director of Technology Maturation, NASA STMD **Power -** **Julie Peck**, JHU/APL, Surface Power Reliability Workshop Report-Out **Michael Provenzano**, Astrobotic Inc., LunaGrid-Lite

AGENDA, CONTINUED

DAY 1

All times are Eastern Daylight Time.

TIME	EVENT	SPEAKERS(S) OR DETAILS
		Autonomy - **Danielle Mortensen**, JHU/APL, Autonomy Workshop Report-Out **Dimi Apostolopoulos**, Protoinnovations, Modular Coordinator Software **Proving Grounds -** **Jodi Berdis**, JHU/APL, Lunar Proving Grounds Workshop Report-Out **Brandon Kirkland**, Redwire Infrastructure Manufacturing with Lunar Regolith **Q&A**
2:30 PM	**Breakout Session -** Minimum Viable & Resilient Infrastructure	
3:20 PM	Break (10 minutes)	
3:30 PM	**Panel**: LuSTR Technology Presentations **Moderator**: Milena Graziano, JHU/APL	**Harri Vanhala**, NASA, Introduction to LuSTR Report-Outs and Recent Awardees **Jin Wang**, The Ohio State University (Power), Flexible DC Energy Router Based on Energy Storage Integrated Circuit Breaker **Arthur Witulski**, Vanderbilt University (Power), Silicon Carbide Power Components for NASA Lunar Surface Applications **Pablo Sabron** (for Alian Wang), Impossible Sensing LLC (ISRU), WRANGL3R - Water Regolith Analysis for Grounded Lunar 3D Reconnaissance **Q&A**
4:30 PM	Lightning Talks	~30 talks, 2 min/talk
5:30 PM	Poster Session & Networking	
6:30 PM	Reception hosted by Moonshot Museum, Astrobotic, and Keystone Space Collaborative (at Moonshot Museum)	

AGENDA, CONTINUED

DAY 2

All times are Eastern Daylight Time.

TIME	EVENT	SPEAKERS(S) OR DETAILS
8:30 AM	Coffee, Networking & Registration	
9:30 AM	Welcome	**Josh Cahill**, LSIC Deputy Director, JHU/APL **Hon. Matt Cartwright**, U.S. House of Representatives **John Thornton**, Astrobotic
9:50 AM	DARPA Announcement	**Introduction -** **James Mastandrea**, LSIC Interoperability Working Group Lead, JHU/APL **Phil Root**, Director, Strategic Technology Office, DARPA
10:20 AM	Keynote NASA Technology	**A.C. Charania**, Chief Technologist, NASA
10:45 AM	Artemis & Ethics Outbrief	**Zachary Pirtle**, Senior Policy Analyst, NASA
10:55 AM	Break (10 minutes)	
11:05 AM	**Panel**: Utilizing Autonomous Robotics and Telerobotics to Establish and Maintain Infrastructure **Moderator**: Justin Starr, CCAC	**Terrestrial Perspectives -** **Shawn Fernando**, Woodside Energy, Remote Operations & Robotics **Nick Paine**, Apptronik, The Apollo Humanoid Robot **Preparing for the Lunar Surface -** **Toyotaka Kozuki**, GITAI USA, GITAI's Challenge to Build Infrastructures on the Moon **Ross Rickards**, Lockheed Martin, Lunar Infrastructure & the Role of Mobility **Ryan McCormick**, Jet Propulsion Laboratory, COLDArm **Q&A**
12:05 PM	Break (5 minutes)	

AGENDA, CONTINUED

DAY 2

All times are Eastern Daylight Time.

TIME	EVENT	SPEAKERS(S) OR DETAILS
12:10 PM	Breakout Session	
1:00 PM	**Lunch Break** (90 minutes) and Moonshot/Astrobotic Guided Tour, Caterpillar Remote Mission Control Stations, GatherTown Virtual Poster/Networking Session	
2:30 PM	**Panel**: Trailblazers & Bridge Makers - CLPS & Artemis Robotics Headed to the Lunar Surface Soon **Moderator**: Josh Cahill, JHU/APL	**CLPS -** **Raewyn Duvall**, Carnegie Mellon University, Iris Rover on Astrobotic's Peregrine **Subha Comandur**, Jet Propulsion Laboratory, CADRE Headed to Reiner Gamma **Trent Martin**, Intuitive Machines, IM-2 Lunar Hopper **Dean Bergman**, Honeybee Robotics, TRIDENT and Other Payloads for Lunar Exploration **Artemis -** **Heather Jones**, Carnegie Mellon University, MoonRanger on Artemis **Q&A**
3:30 PM	Break (10 minutes)	
3:40 PM	LSII & LSIC Updates & Vision for the Future	**Wesley Fuhrman**, JHU/APL LSII Lead **Jamie Porter**, LSIC Director **LSII Team & Annual Goals in Light of Announcements**, JHU/APL
4:15 PM	Closing Comments (e.g., announcement of Caterpillar Best TeleRobotic Operator winner; reminder when tours are departing for Carnegie Mellon University)	
4:30 PM	Adjourn Meeting	
5:30 PM	Bus/Vans Depart for Carnegie Mellon University Tour	

POSTER SESSION

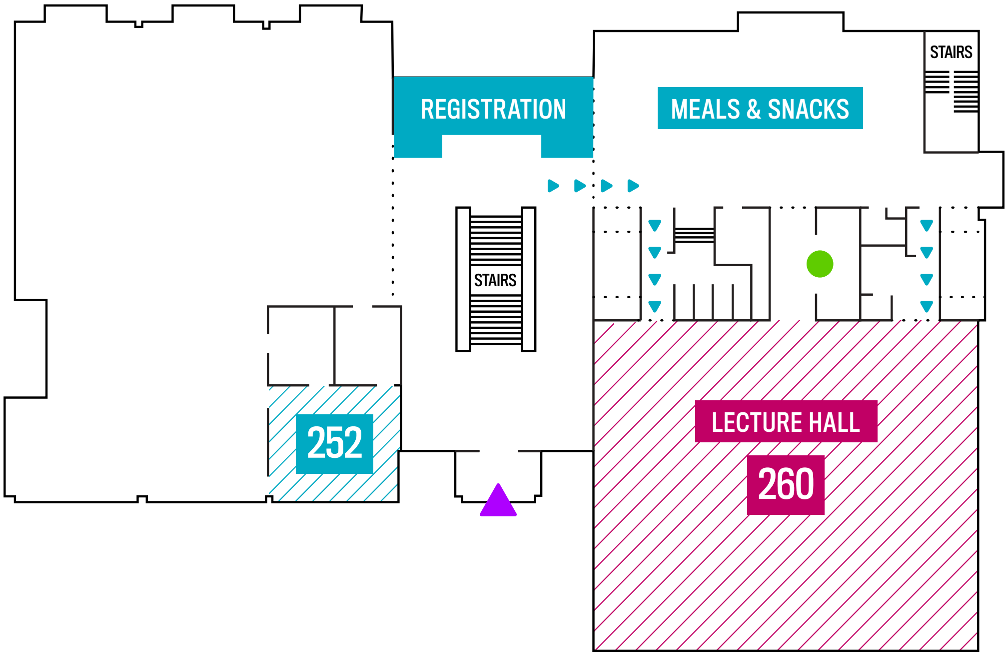
The in-person poster session will be held on Tuesday, Oct. 10, at 5:30 p.m. EDT on the 1st floor of CCAC Foerster Student Services building. Posters can be hung up at any time before the session and can be up for both the Oct. 10 and 11 meeting days.

The online poster session will be held on GatherTown on Wednesday, Oct. 11, at 1:30 p.m. EDT during the lunch session.

MAP

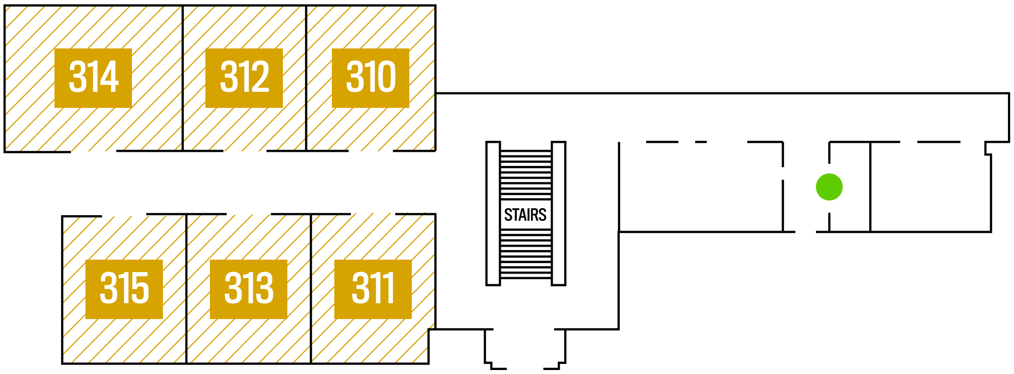
Below is a map of the LSIC 2023 Fall Meeting activities located in CCAC's Foerster Student Services building. The main program will be conducted in the 2nd floor lecture hall, while breakout sessions will be held on the 3rd floor in classrooms 310–315.

2ND FLOOR



▲ ENTRANCE ● ELEVATORS ■ MAIN PROGRAM ■ BREAKOUT SESSIONS

3RD FLOOR



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Innovative Features of NASA's Celestial Mapping System to Support Exploration in the Lunar South Pole.

P. Agrawal[1], M. E. Peterson [1,2], G. M. Del-Castillo[1,2] , I. Lopez-Francos [1,3], G. Mackintosh[1,4] , A. Zuniga[1], [1]NASA Ames Research Center, Moffett Field, CA 94035-1000, parul.agrawal-1@nasa.gov, [2] USRA, [3]WYLE Labs, [4]BAERI.

Introduction: NASA's Celestial Mapping System (CMS) [1,2] is developed to address the need for 3D tools for planetary science investigations, mission planning, in-situ operations, in a 3D-first design constructed around a unified view of a planetary globe. At present CMS provides many critical functionalities that include: 1) equipment planning and optimized placement on Lunar surface 2) line-of-sight (LOS) analysis 3) powerful measurement tools based on 3D terrain with realistic 3D models to represent rovers, astronauts and equipment 4) visualization of derived mapping products (e.g. resource maps), and 5) a data engine for hosting new observations that are not available in other contemporary lunar data tools [1, 3]. CMS is founded on the robust NASA WorldWind globe engines [4]. In near future, users will be able deploy CMS across multiple hardware configurations and platforms, including Windows, Linux, iOS and, Android. Users will also be able to update to the latest imagery and terrain datasets as they are being acquired (in real time) before and/or during the exploration mission. CMS can also consume and analyze data from locally hosted and external sources. It is compatible with Open Geospatial Consortium (OGC) data and file standards and currently integrates datasets from the Astrogeology Science Center of USGS. This includes global and local data acquired from NASA (LRO, Clementine, Lunar Orbiter) and JAXA (SELENE/Kaguya), with capability of integrating more datasets. CMS, with expertise in both the end-user application and planetary engine development can readily adapt to emerging Lunar cartography standards as they develop and become recognized by international geospatial panels.

Overcoming Polar Distortions: 3D geospatial applications traditionally exhibit significant distortions in polar imagery due to several reasons: 1) distortions in the source imagery, 2) incompatible tessellation algorithms at the poles, and 3) map projections. In the lunar context, especially focusing on the South pole, such distortions are unacceptable. The CMS team is exploring solutions to address polar imagery distortion, leveraging new tessellation algorithms and reprojecting data using projections that are better suited for polar scenarios. Fig 1 shows the potential error introduced by different tessellation methods, represented by the red and green circles for Shoemaker crater. There is ~2 Km difference in the placement of the crater.

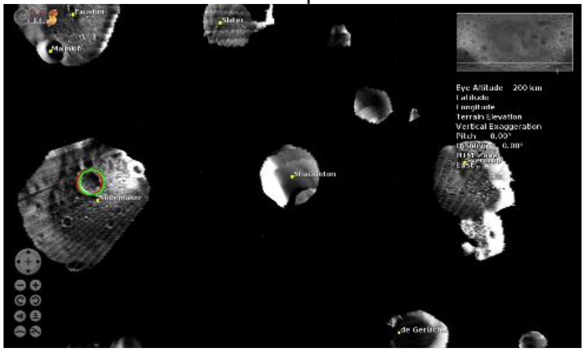


Fig 1: Distortion at Shoemaker crater. Source CMS.

LOS Analysis and Traverse Planning: We've integrated a LOS tool into CMS which analyzes terrain profiles and obstructions to determine visibility for remote observers. Fig 2 shows the viewshed analysis on a permanently shadowed region (PSR) in the lunar South Pole's Nobile region, the site of the upcoming NASA VIPER mission. The PSR layer was generated using images generated by HORUS denoising tool [5]. The yellow pin shows the observer location outside the PSR, with the yellow region representing the visible portion of the PSR. Areas obstructed and not visible for the observer are shown in red. We expanded this analysis to account for varying observer heights and subsequently conducted the viewshed analysis. Combining the different visibility profiles can help designing improved traverses within the PSR.

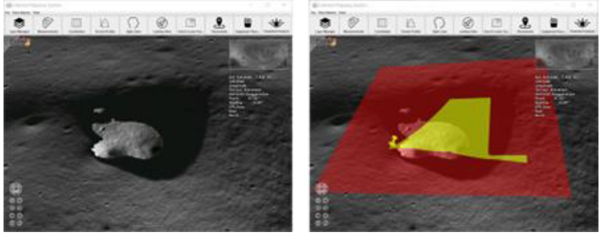


Fig 2: Line of sight analysis within a PSR. Source: CMS

References: [1] https://celestial.arc.nasa.gov [2] Agrawal et. al. "Celestial Mapping System for Lunar Surface Mapping and Analytics", Lunar Surface Innovation Consortium, 2021 [3] Agrawal et. al., "Science Investigations and Exploration in Celestial Mapping System LSSW 17, June 2022 [4] https://worldwind.arc.nasa.gov/ [5] Bickel V. et al. (2021) Nat Commun 12, 5607

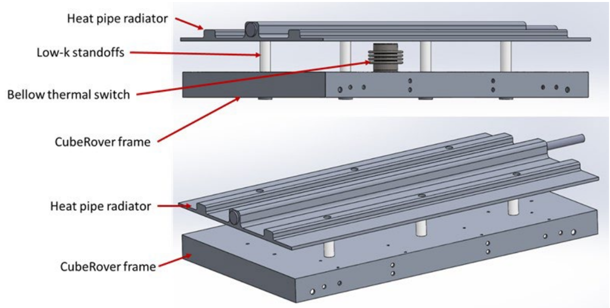
Thermal Control Technologies for Lunar Landers and Rovers.

William G. Anderson[1], Jeffrey Diebold[1], Michael C. Ellis[1], Ion Nicolaescu[1], Nathan Van Velson[1], and James Eckard[2], [1]Advanced Cooling Technologies, Inc. 1046 New Holland Ave., Lancaster PA 17601, [2]Astrobotic Technology, Inc., 1016 N Lincoln Ave, Pittsburgh, PA 15233 (Contact: Bill.Anderson@1-act.com)

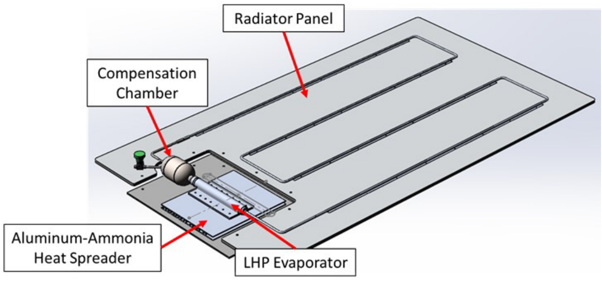
Introduction: The lunar night poses a significant challenge in the thermal management of landers and rovers operating on the lunar surface. This is especially true for long duration missions, in which the on-board electronics of these vehicles must be maintained within their survival temperature range to ensure mission success. As the radiator is sized to reject heat during the lunar day, excessive heat rejection during the low temperature lunar night is unavoidable. One solution to this challenge is a variable thermal link, with a high conductance during the Lunar day, and a low conductance during the Lunar night. Ideally, this link should be passive, since 1 W of electricity throughout the Lunar night requires about 5 kg of extra solar cells and batteries. This poster will describe two such devices: 1. A Two-Phase Thermal Switch, and 2. A Loop Heat Pipe (LHP) with a Thermal Control Valve (TCV).

Thermal Switch for a Lunar Rover: A new passive thermal switch design has been developed and demonstrated that can carry high powers with a high On/Off conductance ratio. This thermal switch design utilizes a sealed flexible bellows that contains a saturated two-phase working fluid. At low temperatures, the saturated vapor pressure within the bellows is low, and the bellows is not in contact with the heat sink. At higher temperatures, the vapor pressure increases, causing the bellows to expand until in comes into contact with the heat sink, allowing heat to be transferred by evaporation and condensation of the working fluid.

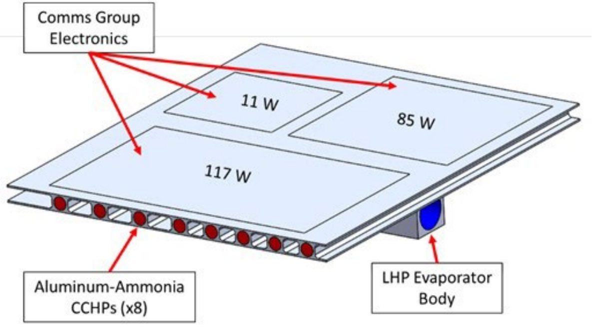
A CAD model of the prototype thermal switch is shown below. It is designed to provide thermal control for the Astrobotic Cube Rover. The thermal switch is currently being fabricated, and will be tested at Astrobotic in late Fall, 2023.



Loop Heat Pipe with Thermal Control Valve for a Lunar Lander: A CAD model of the lunar lander mockup test currently being fabricated is shown below. Heaters representing electronic components will be mounted on the heat spreader panel. A horizontal heat spreader is representative of the horizontal panels of the Griffin Lander. An LHP with TCV will serve as the thermal link between the heat spreader and the radiator panel. The experimental setup will be capable of tilting to simulate adverse orientation.



The LHP with TCV is coupled with a heat spreader with aluminum/ammonia heat pipes. A screen wick is used to allow the heat spreader to work in all orientations. The figure below shows a CAD model of the heat spreader.



The heat spreader with aluminum-ammonia screen wicked heat pipes demonstrated a conductance over 20W/K. The screen wick heat pipes enabled operation up to tilt angles of at least ±5° (±30° on the lunar surface) with negligible effect on performance. The next step is to integrate the heat spreader with the LHP evaporator in order to demonstrate the entire thermal management system. The thermal system will be tested at Astrobotic in late Fall, 2023.

Development & Flight testing of the Advanced Modular Power and Energy System (AMPES) - PEM Fuel Cell for Spaceflight & Lunar Surface Missions. Max Aronow[1] and William Smith[2], 431A Hayden Station Rd. Windsor, CT 06095, maronow@infinityfuel.com

Introduction:

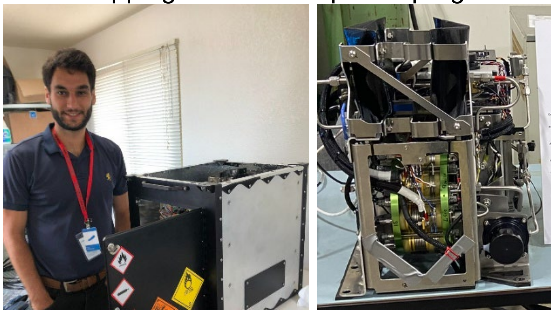
Fuel cell power systems have been a preferred electrical power source for extended crewed missions since the earliest days of manned spaceflight. Gemini, Apollo and the Space Shuttle Orbiter all were powered by hydrogen-oxygen fuel cells. The flight of STS-135 marked the last flight of this generation of fuel cells and NASA lost that capability in 2011 as production ceased with the retirement of the shuttle fleet. However, in 2006 NASA initiated development, at Infinity, of a new generation PEM fuel cell technology using passive water management techniques. This effort built on the Gemini fuel cell water management approaches updating the Gemini technology for advances in materials and controls. Since that date, NASA has continued funding Infinity's development, at the laboratory and prototype level. Infinity's NASA Tipping Point program was formed with the goal to increase the Technology Readiness Level, TRL, of Infinity's fuel cell technology.

This Tipping Point program is funded by NASA's Game Changing Development Program under the Space Technology Mission Directorate in partnership with the NASA Johnson Space Center. Tipping Point's project focus has been the development of a complete system, the Advanced Modular Power and Energy System (AMPES), designed to test the technology, in flight, to advance readiness for future manned flight and lunar surface applications. The focus of this effort has included improvement of stack sealing technology to be compatible with space vacuum, reducing stack mass and development of a flight compatible balance of plant including fluid-mechanical components, controls, reactant storage and thermal control. The goal was to then demonstrate operation of this complete system in micro-gravity via a Blue Origin New Shepard suborbital test flight.

The complete system including the fuel cell stack, autonomous controller, and balance of plant successfully completed EMI testing followed by shock and vibration ground testing at NASA JSC. It was then shipped to Van Horn, TX and installed aboard Blue Origin's New Shepard launch vehicle intended for the sub-orbital test flight. The AMPES system was launched aboard NS-23 from Blue Origin facilities near VanHorn, TX on September 12, 2022.

The AMPES fuel cell flight test called for the system to operate before launch, during boost, during the zero-g portion of the flight and during descent and landing. NS-23 launched normally and proceeded to near Max Q but encountered an anomaly that initiated the emergency escape sequence. The capsule escape system operated successfully and separated the capsule from the booster. The result for the AMPES test article was an unplanned, but very relevant, flight profile. After separation the New Shepard capsule escape system continued to function as designed returning the payload capsule safely to earth allowing the successful recovery of the AMPES. Upon recovery, Infinity determined that the AMPES had survived and operated as anticipated during the entire flight sequence. This included autonomous start prior to the launch and normal operation during descent and landing resulting in relevant data. Following the New Shepard flight, the AMPES system successfully completed thermal vacuum testing at Johnson Space Center. As a result, the overall program, despite the launch anomaly, has advanced the readiness of this technology moving it one step closer to full spaceflight qualification. AMPES is scheduled to fly again on NS-24 this fall 2023 in order to fully demonstrate Infinity's fuel cell technology in a zero-g environment.

This presentation will review the AMPES New Shepard flight test along with other tests and the overall Tipping Point development program.



Max Aronow – Lead Engineer & AMPES Payload

Max Aronow is a systems engineer at Infinity Fuel Cell & Hydrogen. Max oversaw all testing throughout the program and was the primary representative for Infinity at Johnson Space Center. Max graduated from the University of Connecticut in 2019 with a degree in Management Engineering for Manufacturing.

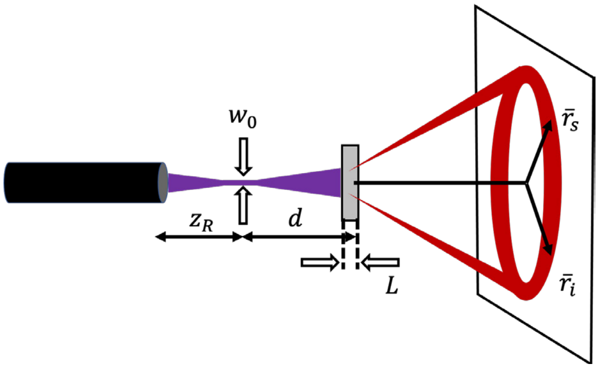
Lunar Temperature Effects on SPDC Polarization Qubit Generation. V.M. Ayres[1], N. Sebasco[1], J. Vetere[1], G. Panda[1], Cordell Mazetti[2], Alejandro Rodriguez-Perez[3] and H.C. Shaw[4], [1]Department of Electrical & Computer Engineering, Michigan State University, East Lansing, MI 48824 USA, [2]Department of Electrical & Computer Engineering, University of Texas at Austin, Austin, TX 78712 USA, Codes 5620 and 5560, NASA Goddard Space Flight Center, Greenbelt, MD, 20771 USA, (Contact: ayresv@msu.edu)

Introduction: NASA has vital interests in responsive and secure optical communication strategies to support initiatives such as Lunar Gateway, a key component of the Artemis program. Quantum communications approaches are strong candidtes to achieve these goals. Quantum communications refer to communication systems that are based on quantum entanglement. Quantum entanglement may be realized using photonic and electronic implementations, with photonic implementations required for free space surface-satellite and satellite-satellite transmissions.

SPDC Polarization Qubit Generation: Spontaneous parametric down conversion (SPDC) is one of the best-tested and therefore reliable methods to generate entangled photons using their polarization states. Nonlinear crystals have 2 optical axes. A strong laser pump (p) beam can interact with nonlinear crystal through its 2nd order susceptibility $\chi^{(2)}$. An incoming short wavelength pump beam photon is absorbed and re-radiated as 2 identical longer wavelength daughter photons (signal (s) and idler (i)). The polarizations and emission directions of daughter photons reflect the constraints imposed by conservation of energy $\hbar\omega$ and momentum $\bar{q}$, referred to as the phase-matching conditions [1]. Coherent spatial overlap of the (displaced) cones of the daughter photon emissions yields the entangled two-photon state $|\psi_{two\ photon}\rangle$ that depends crtically on a phase matching function ϑ_p and an angular spectrum $V(\bar{q}_p)$

Realistic Implementation Issue: Pump Beam Waist Mis-location

Ideal SPDC efficiencies are not high and realistic SPDC efficiencies are further impacted by variations that produce non-ideal phase matching. Several of these can be induced by the temperature variations of elements within the experimental set-up. One of these, laser pump beam-mis-location, is the subject of this investigation. The strong laser pump beam has a Gaussian beam profile with a beam waist w_0 located at the Rayleigh distance z_R. For SPDC daughter photon generation, the beam waist should be located within the nonlinear crystal width L, idealy towards the exit surface. When the beam waist non-idealities happens when the beam waist is mis-located by a distance d as shown (adapted from Ref. [1]), the angular spectrum becomes beam waist postion d dependent:



$$V(\bar{q}_p) = V(\bar{q}_s + \bar{q}_i)$$
$$= exp\left[-\frac{|\bar{q}_p|^2 w_0^2}{4}\right]\ exp\left[-i\,\frac{|\bar{q}_p|^2 d}{2k_p}\right]\ exp^{i(k_{pz}-k_p)d}$$

Conditions to achieve the phase-matching condition have tight tolerances. In this work, we investigate the impact of expected lunar temperature variations on two SPDC sources in the Quantum Communications Laboratory at the NASA Goddard Space Flight Center: β-bismuth barium borate (BBO) and periodically-poled potassium triphosphate (PPKTP). The angular spectrum will be investigated for changes in distance d expected for lunar temperatures 380 K (day) and 100 K (night), with temperature ramp investigations corresponding to changes in latitude from 0° (steepest temperature ramp) to 75° [2]. Theoretical investigations are compared with experimental results achieved using a well-calibrated movable stage to simulate expected changes in d.

References: [1] S.Karan et al, J. Opt. 22 (2020) 083501 (20pp). DOI: 10.1088/2040-8986/ab89e4 [2] PO Hayne, et al, J Geophys Res: Planets 122: 2371-2400 (2017). DOI:10.1002/2017JE005387

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

Electrostatic Sieve Design Effects on Lunar Regolith Simulant Movement and Separation.

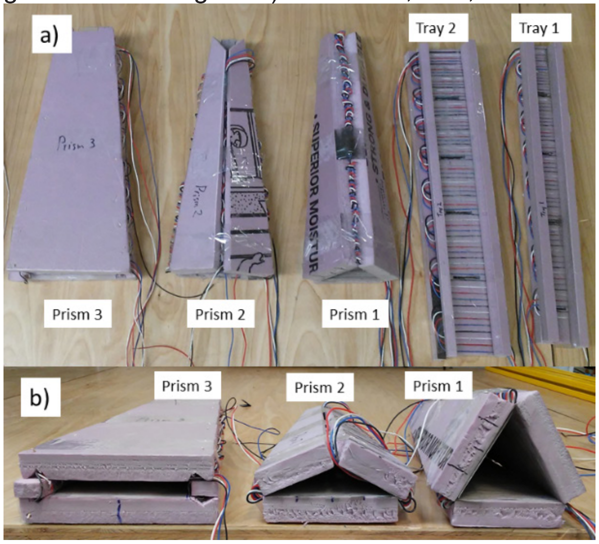
P. Bachle[1], J. Smith[1], F. Rezaei[1], D. Bayless[1], W. Schonberg[1], and D. Han[1], [1]Missouri University of Science and Technology, 400 W. 13th Street, Rolla, Missouri 65409. (Contact: handao@mst.edu)

Introduction: Of the many challenges encountered for effectively utilizing *in-situ* lunar regolith, our research focuses on size sorting and the movement related to that process. We have designed several iterations of electrostatic sieves that attempt to both move particles along an incline and separate the particles by rough size groupings.

The lunar regolith exhibits a wide range of particle sizes [1]. Our goal is to collect only the particles that range from 20 to 200 microns. This size range is selected to prevent choking by fines and yet be small enough to chemically treat for metal extraction without unreasonably long process times.

While most feed systems for processing lunar regolith involve mechanical lifting, our research appears to indicate that silt- to sand-sized particles can be lifted and moved without mechanical handling. By reducing mechanical handling, the dispersal of clinging dust can be mitigated.

Design Elements: The electrostatic sieves were tested for both shape and electrode angle. The shapes include cylindrical, linear, and prismatic. The prismatic cross sections were rectangular (90°), equilateral triangular (60°), and isosceles triangular (30°). The electrode angles tested (in regard to the long axis) were 90°, 45°, and 75°.

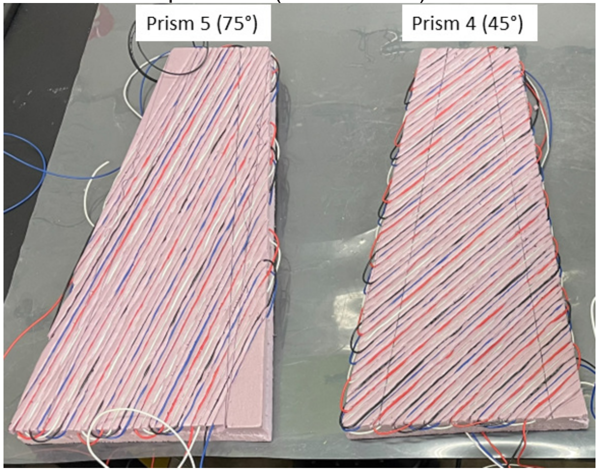


All sieves were roughly 50 cm long. The cylindrical sieve was 1.45 cm in diameter. The linear sieves were 3.7 and 7.5 cm width. The prismatic sieves were 3.7 cm wide at the top (receiving end) and 13 cm wide at the bottom end.

Both the cylindrical and linear sieves were tested with perpendicular slots along the length.

The electrode pitch was 5 mm on all sieves except the linear. The linear sieves varied the pitch with distance from the top (5, 6, 7, 8, and 9 mm pitch every 10 cm of length).

Results: In the early stages of electrostatic sieve tests, an optimal frequency range of 7 to 12 Hz was observed to result in particle movement in the 100-to-500-micron size range. The particles in the sub-100-micron range did not respond well to the tested frequencies (1 to 120 Hz).



Particle movement induced by electrostatics was mostly perpendicular to the electrode. Due to the non-conductive nature of the particles used, it appears that dielectrophoresis is a primary motivation force in addition to electromagnetic travelling waves induced by the 4-phase circuit.

It was observed that a prismatic shape permitted size separation to a limited degree. This was also observed with increasing pitch along the length (pitch increase of 1 mm every 10 cm of sieve length). The largest size separation was observed in the coarse-grained simulants (peak shift of 60 microns), followed by the medium-grained (peak shift of 30 microns). The fine-grained simulants showed a maximum of 10-micron peak shift when separation occurred. However, the optimal range or 20 to 200 microns has not been attained to date.

References: [1] Carrier W. (2006) *The four things you need to know about the geotechnical properties of lunar soil*. Lunar Geotechnical Institute.

Magnetic Separation of Lunar Regolith Simulants: Designs and Challenges.

P. Bachle[1], C. Wood, J. Smith[1], F. Rezaei[1], D. Bayless[1], W. Schonberg[1], and D. Han[1], [1]Missouri University of Science and Technology, 400 W. 13th Street, Rolla, Missouri 65409. (Contact: handao@mst.edu)

Introduction: Separating lunar regolith particles by chemical composition is important to optimizing subsequent metal extraction. Sorting by iron content is a method of separation that is likely attainable in a lunar environment due to the lack of reliance on gravity as the primary motivating force.

Lunar regolith is comprised mostly of plagioclase (diamagnetic), olivine and pyroxene (paramagnetic), and iron micrometeorites (ferromagnetic) mixed with agglutinates [1]. Therefore, designing a lightweight, low power magnetic separator is a goal of our research.

Design: The magnetic drum separator is currently using a dual-drum design. The first drum is attached to a vertical belt with the intent of removing free iron from the simulants. The second drum is attached to a lateral belt with the intent of removing paramagnetic particles from the diamagnetic material.

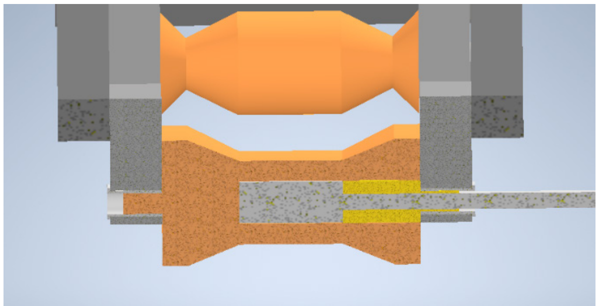


Figure 1. Internal magnet in second drum. Tension drum located at top of figure.

A Frantz Isodynamic Magnetic Separator was used to both determine if diamagnetic minerals could be separated and establish a benchmark for maximum expected separation.

Additionally, a set of 28 different simulants was used that represent separate aspects of lunar regolith. The varied parameters of the simulants are mineral composition (4), size distribution (3), and agglutinate content (2).

Results: It was discovered early on that single magnetic drum separator designs resulted in excessive iron binding with diamagnetics. A primary weak magnet used for iron extracting was then stationed prior to the secondary paramagnetic separator.

During single pass throughs, separation does occur with extensive middlings when an N52 magnet is used in the second drum. However, better separation is attained when an N42 (slightly weaker) magnet is used in the second drum.

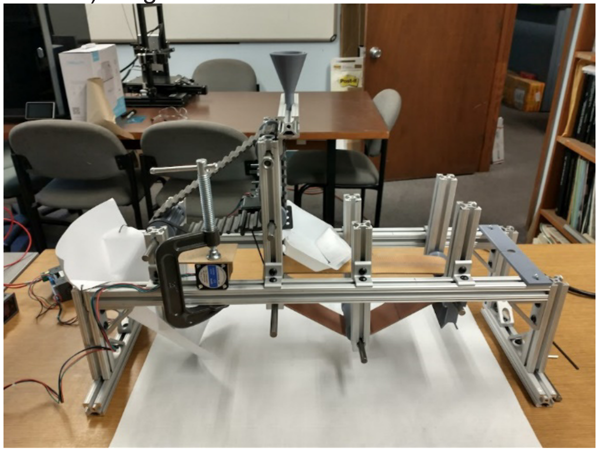


Figure 2. Dual magnetic drum separator prototype. Feed is top center. Primary drum is top center and left. Secondary drum is lower right.

Medium sand- to very fine sand-sized grains (500 to 100 microns) exhibit better separation than course silt- through clay-sized grains (100 microns and under). It was found that the fine particles were very difficult to separate by composition as observed with true lunar regolith [2].

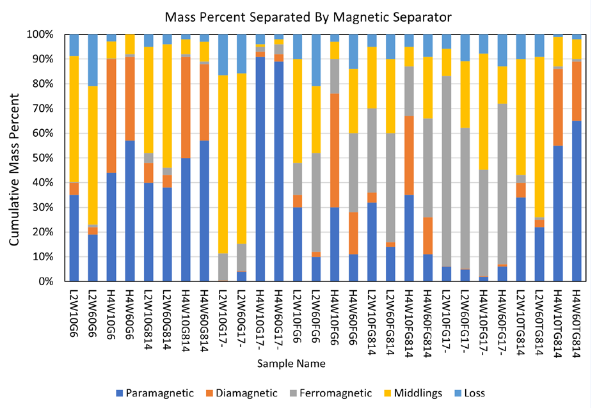


Figure 3. Benchmark separations with all 28 simulants on Frantz separator.

References: [1] Papike, J., Simon, S., & Laul, J. (1982) The lunar regolith: Chemistry, mineralogy, and petrology. *Rev of Geophys, 20(4), 761–826.* [2] Carrier W. (2006) *The four things you need to know about the geotechnical properties of lunar soil*. Lunar Geotechnical Institute.

U-Net Based Semantic Segmentation for Lunar Rock Detection.

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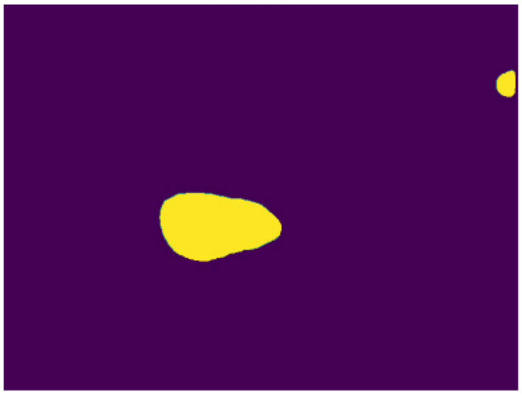
Introduction: With the new wave of extra-terrestrial resource extraction and exploration, navigation on extra-terrestrial surfaces is increasingly important [1]. The NASA LuSTR mission seeks to develop technology for lunar robotic site preparation. This will require accurate real-time navigation and mapping. Since there is no *a priori* information about the environment where the rover will land, surface-level rocks will be used as landmarks. The rover will likely use both RGB cameras as well as LiDAR sensors to detect and uniquely identify rocks.

The innovation proposed is a U-net based semantic segmentation model that is trained on both terrestrial and Apollo images. The difficulties with the lunar use-case are the single-point lighting conditions and the lunar regolith covering the rocks. These conditions serve to saturate the scene and make feature detection hard. This requires the generation of a diverse ground-truth dataset to enable detection independent of lighting conditions or color. We have augmented the dataset by perturbing the images. These images have reduced contrast between background and foreground, shuffled color channels, and spatial transforms. The network is trained with 612 labelled images on a NVIDIA GeForce RTX 3070 to a validation accuracy of 97%. The figure below shows the network detecting a regolith-covered rock. Once the rocks in the scene have been detected, they are uniquely identified using feature detectors, and stored to act as stationary landmarks for navigation.

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

Input Image

Predicted Mask



Power and Ancillary Services Beaming: Trail blazing the mission operations control applications needed to enable scalable, interoperable end-to-end power generation, storage, distribution, and control systems. G. P. Barnhard[1],
[1]Xtraordinary Innovative Space Partnerships, Inc. (XISP-Inc), gary.barnhard@xisp-inc.com

Introduction: In theory, power and ancillary services beaming can both, directly and indirectly, support keep-alive through full operations of surface-based lunar systems. A consortium of commercial and government research lab representatives has come together to support a cooperative, collaborative, and competitive bake-off of power and ancillary services beaming technologies through round-robin testing in some combination of facilities. This effort is frequency agnostic, spanning the range from inductive charging, near field, through far-field transfer, and induced effects using a variety of microwave, millimeter-wave, infrared, through eye-safe optical frequencies.

Catalysts: This effort is being catalyzed by several considerations.

There are emerging requirements for power and ancillary services in multiple venues throughout Cislunar space (i.e., space-to-space, surface-to-surface, space-to-lunar/asteroidal surface, space-to-Earth). The range of services needed likely includes at a minimum (e.g., power transfer; heat transfer; communications (telemetry, command, and instrument data), sensible reflections, position, navigation, and time). The applications include (e.g., remote power transfer (emergency, keep-alive, recharge, mobility, and augment); Interoperable Network Communication Architectures (INCA); autonomous navigation; situational awareness; dust monitoring and mitigation; surface sintering; ad hoc and interferometric network synthesis and synchronization, exploration, prospecting, and pilot plant In Situ Resource Utilization)

Some of these requirements, services, and applications may be best accommodated by beaming technologies using frequencies ranging from microwave, millimeter-wave, infrared, through optical bands. Any use of beaming technologies requires sensing, authentication, authorization, and control (Security), a near real-time characterization of the radiated beam in terms of its components and the reception thereof (Performance), as well as operating parameters, safety considerations, and duty cycle (Availability). End-to-end power systems require power generation, storage, transmission, and load management provisions.

Both power (e.g., batteries, capacitors, superconducting storage rings) and thermal (e.g., waddi, eutectic materials, heat pipes, insulators) energy storage systems supported by power and ancillary services beaming capabilities need to be considered.

Solutions for surviving and operating through the night require integrated power and thermal analysis for design as well as exposed thermal Applications Programming Interfaces (API) and load management controls.

Objectives: The identified catalysts can drive efforts to reduce the systems engineering of power and ancillary services beaming to practice and, in so doing, raise the Technology Readiness Levels (TRL) would seem reasonable and prudent.

The overall objective is to further Technology Development, Demonstration, and Deployment (TD^3) mission development efforts which could benefit from precursor ground testing, which harnesses beaming technologies to demonstrate the ability to meet customer requirements.

References:

[1] Barnhard, Gary P.; Douglas, Seth D., “Bootstrapping Lunar Exploration To Settlement: Power And Ancillary Services Beaming,” IAC-21,C3,2,2,x67037 IAC 2021 Dubai October 26, 2021, https://tinyurl.com/k6jkaphn

[2] Barnhard, G.P. “End-to-End Frequency Agnostic Remote Power and Ancillary Services,” ISDC 2022, Space Solar Power Symposium Arlington, VA May 26, 2022
https://tinyurl.com/ymuvv6bp

(400 Word Compliant Version)

Advancing Space Radiobiology knowledge in view of the humans return to the Moon: Insights from the INFN Roma Sapienza Alpha Magnetic Spectrometer Group. A. Bartoloni[1], on behalf of the AMS SPRB Collaboration, [1]Italian Institute for Nuclear Physics Roma Division, alessandro.bartoloni@cern.ch, (Contact: email alessandro.bartoloni@cern.ch)

Introduction: Space radiobiology is a multidisciplinary field that investigates the biological effects of ionizing radiation on astronauts engaged in space missions. Understanding the health risks associated with human space exploration is crucial for mitigating damages caused by Galactic Cosmic Rays (GCRs) and solar radiation. GCRs pose a significant radiation exposure risk in space, making it imperative to assess the potential health risk resulting from GCR particle exposure.[1]

The INFN Roma Sapienza Alpha Magnetic Spectrometer research group is at the forefront of research in this area, actively studying the risk evaluation induced by GCR radiation and this talk will make the point of the last 5 years of research.[2-5]

It will be presented the enabling research that we did on the dose effects models and relationship as well as theoretical framework for modelling the Non target effects due to the space radiation, a crucial topic to assess the carcinogenic risk in space due to space exploration of the deep space especially on view of the humans return to Moon.[6-7]

The roles of the data collected by the astroparticle experiments operating in space will be clarified, with a particular focus on mid and heavy nuclei components of space radiation.

Recently also a collaboration with different research institute is arising to notice is the one with the National Institute for Laser, Plasma, and Radiation Physics (INFLPR) in Bucharest to explore the potentiality to reproduce space radiation conditions through ground experiments is explored by employing Laser Plasma Accelerators. These devices can generate a diverse array of particle beams, including electrons, protons, neutrons, ions, and photons, by tuning various parameters.[8]

References:

[1] John R. A., et al., (2022). *Safe Human Expeditions Beyond Low Earth Orbit (LEO).* NASA/TM-20220002905 NESC-RP-20-01589

[2] Aguilar, M., et al. (2021). *The Alpha Magnetic Spectrometer (AMS) on the international space station: Part II — Results from the first seven years.* Phys. Rep 894, 1-116. 10.1016/j.physrep.2020.09.003.

[3] Bartoloni A., et al (2020) *Radiobiology with the Alpha Magnetic Spectrometer (AMS02) experiment on the International Space* Station in proceedings of RAD 8 - 8th International Conference on radiation in different fields of research June/2020

[4] Bartoloni A. et al,(2021) *Can high energy particle detectors be used for improving risk models in space radiobiology?* in proceedings of the Global Space Exploration Conference 2021 (GLEX2021) Jun 2021.

[5] Bartoloni et al, (2022). *High energy Physics Astro Particle Experiments to Improve the Radiation Health Risk Assessment for Humans in Space Missions.* EPS-HEP2021 398, 106. 10.22323/1.398.0106

[6] Strigari,et al L.. (2021). *Dose-Effects Models for space radiobiology: an overview on dose effect relationships,* Front. Public Health 9, 733337. 10.3389/fpubh.2021.733337.

[7] Guracho A.N., et al (2023), *Space radiation-induced bystander effect in estimating the carcinogenic risk due to galactic cosmic rays,* Journal of Mechanics in Medicine and Biology (JMMB), https://doi.org/10.1142/S0219519423400237

[8] Hidding B., et al (2011) Laser–plasma-accelerators—*A novel, versatile tool for space radiation studies,* Nuclear Instruments and Methods in Physics Research A 636 31–40

Beyond Borders: Uniting Nations in Lunar Exploration - A Recap of the Space Summer School 2023.

A. Bartoloni[1], [1]Moon Village Association, Alessandro.bartoloni@moonvillage.associations.org, (Contact: alessandro.bartoloni@cern.ch)

Introduction: The Moon Village Association Italian associates and institutional partners successfully organized a remarkable Space Summer School in Italy on July 24th and 25th, 2023. This event coincided with the celebration of International Moon Day 2023. The school was conducted in a hybrid mode, blending in-person and virtual participation, making it accessible to a wide audience.[1]

With an overwhelming response, more than 70 individuals registered for the event, showcasing the significant interest and enthusiasm among stakeholders from various backgrounds. The school provided an unparalleled networking experience, bringing together speakers and attendees from over 10 different countries across Europe, Asia, America, and Africa

As a NGO, the MVA's primary objective is to establish a permanent global forum for governments, industry, academia, and the public invested in lunar exploration. With over 600 participants the MVA embodies a wide spectrum of technical, scientific, cultural, and interdisciplinary fields.

The IMD2023 is an annual event celebrated worldwide to raise awareness about the status and future prospects of sustainable Moon exploration and utilization.

The experience of organizing and leading the school event, along with the participants' follow-up three months after the school, will be documented in this talk. This documentation seeks to illustrate the school's role in addressing global societal issues and understanding the significance of such activities in tackling challenges related to the Moon and beyond.

Overall, the school proved to be a resounding success, leaving a lasting impact on the international lunar exploration community and nurturing a collective vision for humanity's future in space.

The Moon Comes to Mojave: Testing Emerging Technologies at Astrobotic's Lunar Surface Proving Ground.

Sean Bedford, Astrobotic, 1752 Sabovich St, Mojave CA. (sean.bedford@astrobotic.com)

Introduction: Astrobotic will debut its Lunar Surface Proving Ground (LSPG) this fall. The LSPG is a 100m x 100m high-fidelity test field that will mimic the topography and optical properties of an actual landing site at the Moon's south pole. This unique environment is located at Astrobotic's test site in Mojave, CA, and will primarily supplement Astrobotic's flight testing services aboard its *Xodiac* vertical-takeoff, vertical-landing (VTVL) rocket lander.

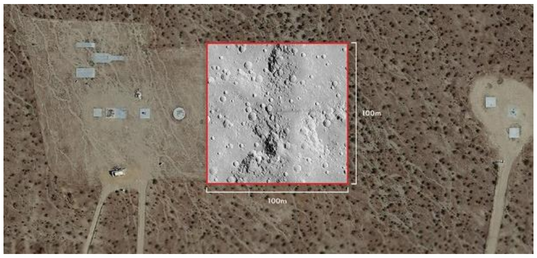


Fig. 1: The LSPG next to Astrobotic's test site

Features: The LSPG simulates a real landing site at the lunar south pole. The surface includes craters, mounds, and other lunar features formed from a mix of concrete and stucco to provide realistic optical characteristics. The LSPG topography is based on an actual map of the lunar surface scanned by Astrobotic's LunaRay system, which is being used to inform flight plans and detect hazards for Astrobotic's upcoming Griffin Mission 1.

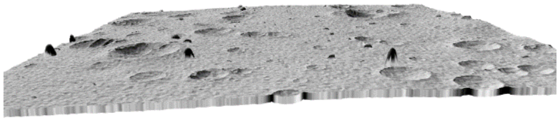


Fig. 2: Representative LSPG lunar terrain

Flight Testing: Astrobotic has a rich heritage of flight testing on VTVL reusable rockets thanks to its acquisition of Masten Space Systems. Its *Xodiac* rocket flies profiles that accurately simulate lunar approach, descent, and landing and can also be used to test plume-surface interactions, as it has done for payloads like UCF's Ejecta STORM.[1] *Xodiac* has completed over 150 flights with 100% mission success. It can be rapidly reused and has flown as many as five flights in a single day.

Xodiac is particularly well suited to fly GNC and avionics payloads, thanks to its Sensei™ hypervisor, which enables closed-loop testing that allows a payload to interact with the flight computer in real-time and effectively steer the rocket. *Xodiac* and its predecessors have tested navigation systems for customers like Draper[2], JPL[3], and Psionic[4]. Astrobotic tested its own TRN system on these rockets to prepare it for lunar use during *Peregrine Mission 1* and *Griffin Mission.* Astrobotic also plans to fly its hazard detection and avoidance system on *Xodiac* next spring.

Fig. 3: *Xodiac* in flight

The LSPG complements *Xodiac's* lunar landing simulation by providing a realistic environment in which to test these high-priority technologies.

Upcoming Campaigns: The LSPG will debut as a simulated lunar environment for NASA's Nighttime Precision Landing Challenge, during which three winning teams will demonstrate sensors for mapping terrain and guiding safe lunar landings in darkness.[5] Astrobotic will then make the LSPG available for commercial and university customers. The LSPG will also play host to NASA's 2024 TechRise Challenge, which will fly payloads from student teams in grades 6–12.[6]

Other Applications: Beyond flight testing, the LSPG's can serve as a proving ground for rovers, surface infrastructure, and wearable technology for astronauts. Its realistic lunar topography can also be used to examine the effects of the extreme lighting conditions found at the lunar poles.

References:

[1] P.T. Metzger et al., *Ejecta Sheet Tracking, Opacity, and Regolith Maturity (Ejecta STORM): An Instrument for Lunar Landing Plume Efects and Dust Dynamics* (2021), 52nd Lunar & Plantary Science Conference; [2] Draper, Press Release: *A New Way to Navigate to Your Next Moon Landing* (2019); [3] N. Trawny et al., *Flight Testing of Terrain-Relative Navigation and Large-Divert Guidance on a VTVL Rocket* (2015), AIAA; [4] Psionic,Press Release: *Psionic NDL Test with Masten Space Systems* (2020); [5] NASA, Press Release: *NASA TechLeap Winners Advance Technology to Aid Lunar Landings* (2022); [6] NASA, Press Release: *NASA Challenges Students to Fly Earth and Space Experiments* (2023).

Lunar Power and Dust Tolerant Distribution.

D. Bergman[1], E. Cloninger[1], B. Van Ness[1], R. Crum[1], K. Zacny[1], M. Okandan[2], J. Wilson[2], K. Rouhani[2], and K. Hell[2], [1]Honeybee Robotics LLC, 2408 Lincoln Ave, Altadena CA 91001, [2]mPower Technology, 5901 Indian School Road, NE, Albuquerque, NM 87110. (Contact: dxbergman@honeybeerobotics.com)

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

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

LAMPS is a deployable solar panel system allowing operation 10s of meters above the ground and generating 10s of kW. LAMPS, in its current architecture, is designed to operated 8-18 m above the ground and provide 10 kW of electrical power, assuming various system level and solar array inefficiencies. This extended height, deployed at certain locations on the Lunar surface, will allow LAMPS to operate with a drastically reduced period in darkness, of around 5 Earth days or less.

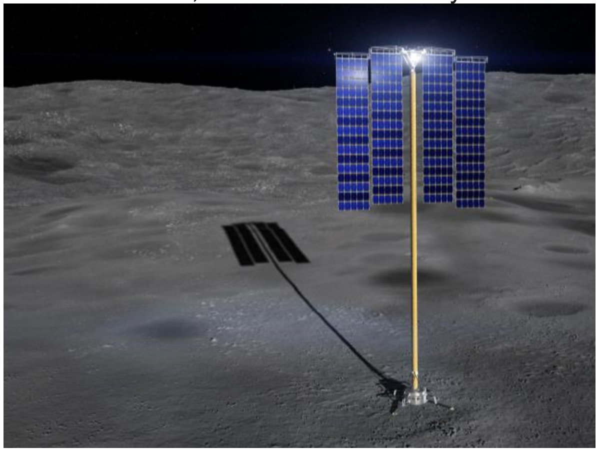


Fig 1. LAMPS 10kW solar array along with HBR's dust tolerant connectors provide the basis to power the Moon.

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

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

Dust Tolerant Connectors (DTC): While it is imperative for LAMPS to be dust tolerant, it is necessary for the robotic and human systems connecting to the power grid also have a robust dust tolerant interface. HBR has been developing for decades and is now in the process of standardizing the connector for lunar use.

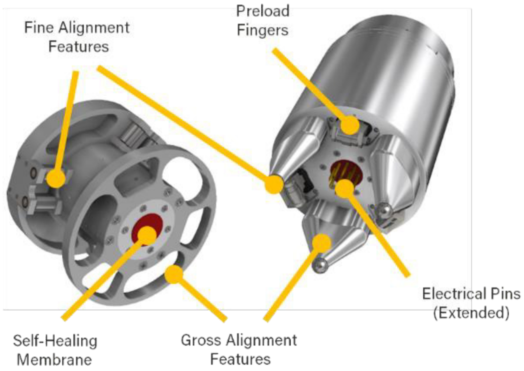


Fig 2. DTC to reliably distribute power around the Moon.

HBR's Goal: It is HBR's mission to provide a robust power grid anywhere on the Moon and enable sustained lunar economy.

ACRE: Autonomous Casting RovEr. A System for the In-Situ Heating and Casting of ISRU-Derived Feedstocks for the Remote Production of Metal Matrix Composite Lunar Roads and Landing Pads.

J. Berkovich[1], J. Rocher[2], B. Taalman[1], T. Abbott[2], X. Castaneda[2], J. Chang Stauffer[2], L. Fahrney[3], I. Falck[3], M. Gao[2], R. Goldenson[2], S. Grayson[2], D. Guo[1], V. Gupta[4], F. Ireland[2], E. Kloster Filho[2], C. Layden[1], E. Liu[2], D. Lynch[2], Z. Muller-Hinnant[2], T. Nanoff[2], C. Ott[1], M. Queen[2], L. Warlick[1], I. McCue[1]. [1]Dept. of Mat. Sci. and Eng., [2]Dept. of Mech. Eng., [3]Dept. of Chem. Eng., [4]Dept. of Comp. Eng., McCormick School of Engineering, Northwestern University, Evanston, IL, USA 60208. (Contact: jaime528@mit.edu)

Introduction: The establishment of a lasting human lunar presence necessitates the large-scale construction of roads, landing pads, and other critical infrastructure over vast areas of the lunar surface. Landing pads are essential to ensure that the propellant exhaust of landing vehicles does not accelerate loose lunar regolith to hazardous velocities. Furthermore, roads will be pivotal to enable safe and efficient traversal of the lunar surface to reach resources (especially water ice) that are distanced from the primary lunar settlements.

The construction of such infrastructure requires a manufacturing system with the capacity to produce substantial volumes of high-strength ISRU-derived material efficiently, reliably, and autonomously. We propose ACRE: Autonomous Casting RovEr to meet this need through the in-situ casting of ISRU-derived feedstock materials. ACRE functions by heating feedstock to a liquid state before depositing batches of the molten material directly into molds formed on the lunar surface by the rover's plow as it drives along. Casting is uniquely suited to early-stage lunar manufacturing due to its innate versatility, robustness, and ability to produce high-quality components from a wide range of potentially available materials. Furthermore, ACRE packs its entire manufacturing process (energy collection, heat generation, feedstock storage, deposition, and mold forming) into the form factor of a self-sufficient and mobile rover, enabling it to autonomously operate for extended periods of time without astronaut involvement.

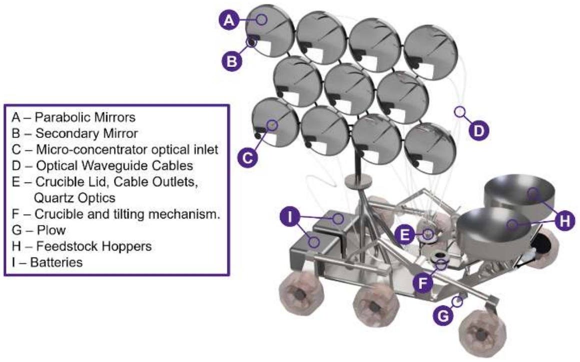


Figure 1: Schematic Overview of the ACRE System

Optical Waveguide Solar Power System (OWSPS): The energy for batchwise heating of the feedstock carried in the rover is provided by the OWSPS system, which uses an array of parabolic mirrors to concentrate the powerful and nearly constant solar rays of the lunar south pole into bundles of Optical Waveguide (OW) cables. The OWSPS will enable heating and deposition directly at the point of use, enabling safe, autonomous construction across vast areas of the lunar landscape with minimal astronaut involvement.

Crucible: The OW cables channel the concentrated solar rays directly into an insulated crucible which ensures that the heat provided by the OWSPS can be sufficiently accumulated to reach target casting temperatures. The crucible design features inner and outer shells of robust alumina ceramic surrounding an insulating layer of zirconia.

Regolith Furrowing and Casting: The shape of the rover's plow (including mold depth, mold width, draft angle, and anchoring shape) can be easily exchanged to optimize for the casting of a particular product. Natural wicking of the deposited liquid feedstock into the powdery regolith mold will help anchor the cast structures.

Metal Matrix Composite Fabrication: ACRE's feedstock will contain a mixture of refined metal and raw lunar regolith to form a precipitate-hardened Metal Matrix Composite (MMC). Aluminum is the preferred refined metal due to its lower melting temperature (for faster heating), proven compatibility for casting in regolith molds [2], and availability via the planned refining of lunar anorthite [3]. The fraction of raw regolith in the MMC will be maximized to reduce the need for more resource-intensive refined metals, thus accelerating the rate and scale of lunar infrastructure development.

Acknowledgement: This work is supported by NASA's Space Technology Mission Directorate's Game Changing Development Program through the 2023 BIG Idea Challenge.

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Using Generative AI for Lunar Image Denoising. Kelsey D. Buckles[1], Kris Verma[1], Steven DeLessio[1], Ramon Hinojosa[2] , [1]NASA Marshall Space Flight Center, Huntsville, AL, 35811, [2]Texas A&M University College Station, TX 77843 (Contact: Kelsey.D.Buckles@nasa.gov)

Introduction:

As NASA prepares to return humans to the moon the need for near-instant image and video denoising will become vitally important to decision making [1]. One of the use cases for video denoising will be for landing leg attenuation on the Human Landing System during Lunar descent. Instantaneous Clarity of Ambient eNvironment Capability (ICAN-C) uses Marshall Space Flight Center (MSFC)'s optical technology and Artificial Intelligence/ Machine Learning (AI/ML) to improve scenarios of obscured or hazy vision.

The short-term motivation is to improve the visual clarity of lunar terrain based on HLS needs. There is no other similar technology on the market today. Using a custom training data set for our AI/ML models, this system is best suited for lunar and Martian operations; however, the neural network can be retrained to be useful on any soil or weather conditions (i.e., blowing southeastern US clay vs Saharan dust vs snow).

ICAN-C has the endorsement of the NASA Dust Mitigation Stakeholders Forum and has matured from TRL 1 to TRL 3 in one year. The current iteration of ICAN-C can detect blowing regolith and the associated neural network is structured to eliminate identified obstructions. Next steps are to bundle the software and cameras into a light-weight package and deploy it on a drone in the MSFC Lunar Regolith Terrain to demonstrate the instantaneous capability of ICAN-C.

Digital Formats:

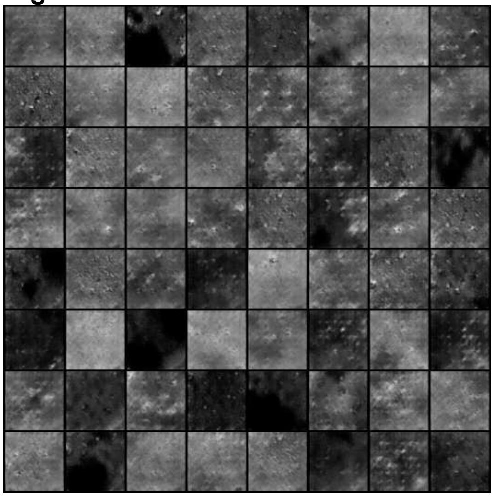

Figure 1 AI Generated lunar terrain after 368 iterations, trained on Clementine Spacecraft images.

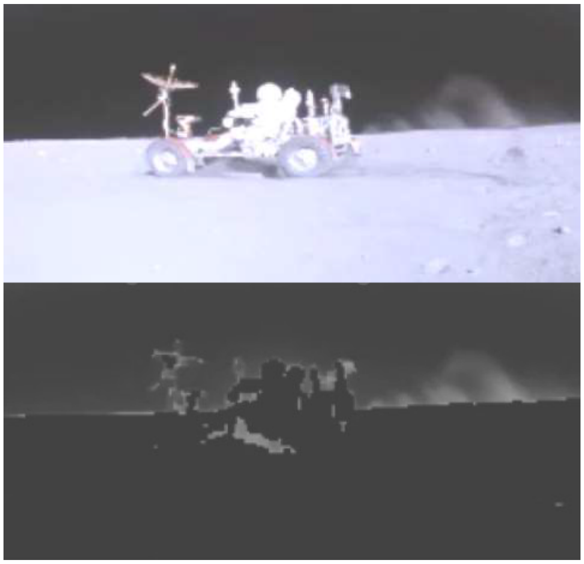

Figure 2 Apollo 16 EVA footage original (above), and dust detected(below)

References:

[1] Maynor, S.B. (17 October 2022). Moon to Mars Surface Systems and Technologies [PowerPoint presentation]. Marshall Partnerships Forum, Marshall Space Flight Center Redstone Arsenal, Alabama, United States. https://ntrs.nasa.gov/citations/20220015553

Title: Virtual Environment for Collaborative Lunar Explorations (VIRCLE).

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Abstract: Many countries are racing to explore the south pole of the moon. This presents opportunities for collaboration and sharing of resources to reduce costs. The Artemis Accords, signed by 28 countries, outline the principle of interoperability. With more government agencies and private companies involved in lunar exploration, it is challenging to establish and maintain interoperability between many entities.

This paper presents a shared virtual environment for collaborative lunar explorations. The environment provides high-fidelity physics-based model of the lunar terrains for partners to jointly design and test lunar missions in a shared environment to ensure interoperability. This realistic virtual environment enables testing of human-robot and robot-robot interactions. It could also provide the needed shared datasets for the entire community to train AI models for lunar autonomous systems. Using a common benchmark in this environment, it could help evaluate different systems' performance. By pairing the virtual environment with a reconfigurable physical testbed, this integrated system could provide digital twins to improve lunar operations and enhance reliability.

In partnership with the NASA-funded Autonomy Research Center for STEAHM (ARCS) at the California State University, Northridge (CSUN), a team at the Jet Propulsion Laboratory (JPL) is developing the prototype VIRCLE environment to support testing of teaming between autonomous rovers exploring the lunar south pole. VIRCLE uses an open metaverse approach based on the Nvidia Omniverse software platform. Data from the Lunar Orbiter Laser Altimeter on NASA's Lunar Reconnaissance Orbiter (LRO) was imported into Omniverse to create the initial lunar landscape. Due to the limited resolution of the LRO data, high-definition lunar terrain and rocks were created using the 3ds Max software and automatically added to the metaverse using a VIRCLE tool (Figure 1). Adobe Substance was used for texturing. The Omniverse handles physics, movement, and 3D visualization using the interchangeable Universal Scene Description (USD) format. A summer internship project titled Moonwalker [1] was developed by a group of interns in 8 weeks on VIRCLE. With help from NASA JPL's CADRE team, the CADRE rover model was imported into the metaverse (Figure 2). Using Chrono physics-based modeling software from the University of Wisconsin-Madison, the team developed a differentiable physics model to accurately predict the behavior of the rover traversing lunar regolith (Figure 3). To support astronaut's immersion in the VIRCLE environment, Microsoft HoloLens was used to provide augmented reality capabilities for human to interact with the virtual test environment (Figure 4). A reconfigurable physical testbed matching the virtual environment is under construction at the ARCS. This testbed will be able to validate the results from the virtual environment. The team plans to open source the Moonwalker software tools and use the Nvidia Graphics Delivery Network to enable distributed high-fidelity 3D interactions across the Internet so that the lunar exploration community can collaborate, contribute, build, and test together.

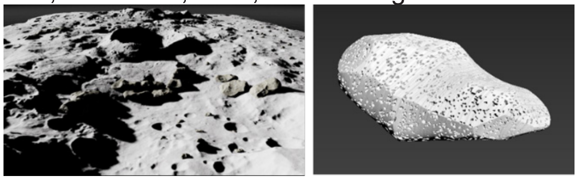

Figure 1: Terrain and model creation

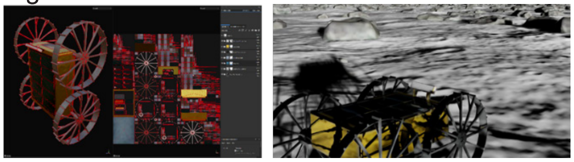

Figure 2: Import rover model into VIRCLE

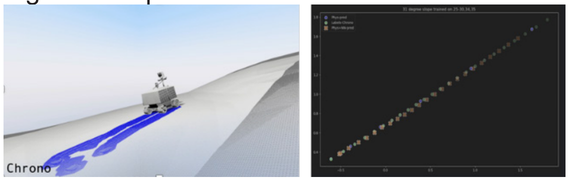

Figure 3: Differentiable Physics Model

Figure 4: Augmented reality capability and digital twins integration with ARCS physical testbed

[1] Moonwalker video, https://www.youtube.com/watch?v=E0Rz0ZbwhJY&t=337s

On the Need for a Virtual Lunar Autonomy Testbed. C.S. Dickinson[1] and P. Grouchy[1], [1]MDA 9445 Airport Rd, Brampton, ON, Canada (Contact: cameron.dickinson@mda.space)

Introduction: A key goal of Artemis is to establish a base camp on the south pole of the moon. Achieving a sustained presence on the lunar surface will require innovations across myriad disciplines, including material and building sciences, robotics and sensors, and autonomy. While low-TRL technologies can be developed in isolation, to achieve higher TRLs, the various components will need to be assembled into systems capable of completing the complex tasks required to construct and maintain Artemis Base Camp.

Real-world testing at lunar analog sites is infrequent owing to it being costly and challenging to coordinate among many diverse teams. In addition, the process of connecting the various components will be a major challenge that, if not planned for and managed from the early days of the project, could result in significant delays and costs. Finally, when comparing the solutions of different teams for a given element of the system, virtual testbeds will be essential for producing quantitative metrics to enable apples-to-apples comparisons without the need for costly real-world testing.

To address the above challenges, we propose the development of the Lunar Autonomy Testbed for Technology Exploration (LATTE), a modular, open source virtual sandbox that will enable cross-team and cross-discipline collaboration on technologies for a sustained human presence on the moon.

Related Work: NASA's Ocean Worlds Autonomy Testbed for Exploration Research and Simulation (OceanWATERS) is an open-source project whose stated goal is to promote the development of autonomy for robotic missions to ocean worlds such as Europa, Enceladus, and Titan [1]. OceanWATERS has already enabled research demonstrations, including for autonomous sampling site selection [2].

LATTE: The four main components of the Lunar Autonomy Testbed for Technology Exploration (LATTE) are Assets, Simulators, Algorithms, and the ConOps Library. These components are linked together via strictly managed Interfaces.

Assets. Any proposed physical object that is not currently present on the lunar surface is considered an Asset in LATTE. This includes robotic hardware and tools, sensors, materials and structures (either from Earth, or manufactured *in situ* on the moon), and human agents.

Simulators. Fast, high-fidelity simulators are an essential component of any virtual testbed. Given the diverse nature of the technologies needed for Base Camp, there will need to be several different simulators in LATTE, including visual and point-cloud simulators, physics simulators for regolith and other materials' behaviors, and robot and structure dynamics. These simulators could be used for both testing and validation of systems and subsystems, as well as for creating large, labelled datasets for offline testing and machine learning. Simulators will need to be validated against real-world data.

Algorithms. Given the complex nature of the tasks at hand, a variety of categories of algorithms will need to be explored and refined, including autonomous, tele-operated, and hybrid control, system health monitoring, perception, and planning.

ConOps Library. To evaluate and compare the various assets and algorithms, a collection of relevant conops will need to be devised. A given conops will specify which types of assets, algorithms, and simulators are required, the tasks that need to be completed, and how performance on these tasks will be quantified (metrics). For any given conops, a leaderboard can be maintained to track the top performing assets and algorithm implementations for that task.

Interfaces. Given the proposed open source nature of LATTE, anyone could submit new assets, simulators, algorithms, and conops. The key to enabling contributions from the community is a strictly defined and managed set of interfaces between the various components of LATTE. This will allow for changes to a single element, such as adding in a new type of sensor, a novel autonomous control algorithm, or an improved regolith physics simulator, without breaking the other assets, simulators, and algorithms already operational within the system. In addition, by implementing these same interfaces in the physical counterparts of the virtual hardware, algorithms and conops will be readily transferable to real-world deployments.

References: [1] Catanoso, D., et al. (2021) *2021 IEEE Aerospace Conference* 1-11. [2] Thangeda, P., and Ornik, M. (2022). *2022 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS)*, 4120-4125

Construction of Lunar Surface Structures Using Regolith Filled Sandbags. C. S. Dickinson[1], A. E. Dinkel[2] R. Emami[3], J. Empey[4], Theodora Girgis[3] P. Grouchy[1], R. Mukherjee[5], K. McIsaac[6], P. Maghoul[7], M. Montaño[8], T. Newson[6], A. Polit[2], S. Tuohy[1], W. Watson[1] and J. Thangavelautham[2]. [1]MDA 18050 Saturn Lane, Suite 200, Houston, TX, USA [2]University of Arizona, 2300 E 15th St, Tucson AZ, USA [3]Univeristy of Toronto, 160-500 University Avenue, Toronto ON, Canada [4]University of Waterloo, 200 University Avenue West, Waterloo ON, Canada [5]JPL 4800 Oak Grove Drive, Pasadena, CA, USA [6]Western University, 1151 Richmond Street, London ON, Canada [7]Polytechnique Montréal, 2900 Edouard-Montpetit Boul, Montreal QC, Canada [8]Embry-Riddle Aeronautical University 3700 Willow Creek Road, Prescott, AZ, USA
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Introduction: NASA's Artemis program has set forth an ambitious plan to return humans to the Moon [1]. It is expected that the return of humans will call for the development of a semi-permanent or permanent base on the Moon. Site preparation and construction methods that can be adapted to changing site conditions and enable base mobility would be ideal because they reduce the overall mission planning constraint and minimize end-structure variability.

We are investigating the use of regolith filled sandbags, which are simple, multifunctional building blocks. Thes can be used in a wide varidety of applications such as berms, landing pads, radiation shelters, ballast (e.g. solar towers), and in future habitat construction [2]. Their modular design, their modest upmass to launch vehicle mass constraints, and ability to be reused, make them a low cost, attractive option for early lunar structures.

Goals: A demonstration mission to the lunar surface is currently being considered, with the goal of constructing a simple berm. This allows for the validation of several technologies such as: regolith excavation, regolith bagging, construction using a building block architecture, as well as the measurement of radiation effects (both protected and unprotected by the berm) and any lunar seismic activity.

A demonstration mission such as this woud be the first step in creating larger structures, that would require increasing knowledge of lunar civil engineering, and could allow for a wide variety of architectures for any permanent or semi-permanent robotic and astronaut habitats.

Mission Breakdown: The mission architecture being considered has been broken down into: regolith excavation, regolith bagging, structure construction, and structure verification.

Regolith excavation involves not only removing material from the surface, but also sorting out any large materials (e.g. impact ejecta littering the surface) [3]. Several methods were considered including rotating drums, mechanized scoops, and shovel based technologies.

Regolith bagging will create the "sandbag" units (called here: Regolith Containment Units or RCUs), as well as manipulate the completed RCU for transfer to the construction element. Several bag materials are being considered, as they must be durable enough to contain the regolith, but must also be sealable while exposed to its abrasive properties.

Construction involves manipulation of the completed bag into a logical "building block" architecture. The bags must be carefully laid, and must contain locking features to avoid slippage.

The Verification step will provide some assurance that the bags are properly stacked, in a way that they will not put undue stress on other portions of the structure and to ensure that they could withstand any lunar seismic activity. This could be achieved through both visual means and "smartbag" technologies [4].

Future Applications: Once demonstrated, the sandbag building methods used to build a simple berm could be applied to larger and more complicated strucutures such as full blast berms, landing pads, adobe domes, and rover shelters.

References: [1] Creech, S et al., (2022) *IEEE Aerospace Conference, Big Sky, Montana, USA.* [2] Thirupathi, A et al., (2022) *Proc. 18th Biennial Int. Conf. Engineering, Science, Construction, and Operations in Challenging Environments, Denver Colorado, USA* [3] Thangavelautham, J., (2017) *Robotica. 35, 12,* p. 2330-2362. [4] Xu Y. et al. (2023) *8th Biennial International Conference on Engineering, Science, Construction, and Operations in Challenging Environments*.

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

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

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

Problem: The low temperature performance of lithium batteries is limited by several factors: (1) the conductivity of the electrolyte; (2) the resistance of the solid electrolyte interface (SEI) or the cathode electrolyte interface (CEI); and (3) the charge transfer resistance of the SEI and/or CEI (moving lithium ions into and out of the solid electrodes).

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

Solid-liquid interfaces in lithium batteries can suffer from slow lithium ion transfer across this boundary, especially when cold. The typical solution to this problem is to add an ionically conductive additive to form an SEI or a CEI *in situ* during cell formation, or to add an artificial SEI / CEI prior to cell assembly to promote lithium diffusion between electrodes and the electrolyte (and to prevent unwanted side reactions). In many cases the artificial SEI / CEI is a polymer. However, the polymers typically cannot perform well in wide temperature ranges expected on the Lunar surface (even for partially temperature-regulated housings or instruments). The materials used for artificial SEI's / CEI's either melt or dissolve when too hot or they become non-conductive when too cold. Advancements that address battery operation at extreme temperatures, combined with high specific energy are still critically needed.

Solution: Our solution to make rechargeable lithium-ion batteries that operate in extreme temperature environments is based on a new, stable, nanostructured polymer that serves as an artificial SEI / CEI that solves the poor lithium conductivity at the solid-solid interphases in high energy density batteries at -40 °C to -60 °C. The same artificial SEI / CEI also provides some discharge capacity at even -80 °C, but the primary focus of this work is to take full advantage of electronics rated to -55 °C. Prototype batteries retain 75% of the room temperature capacity and specific energy of the battery when operated at -40 °C (and still maintain close to half of the capacity at $^{-}$55 °C).

In this project TDA Research is developing and testing a proprietary [2],[3] artificial SEI / CEI for NMC 811 cathodes combined with lithium metal or Si/C anodes. Our artificial SEI / CEI performs well at low temperatures because it has both a high lithium ion conductivity, combined with a very low charge transfer resistance, and it has a temperature vs. conductivity behavior similar to solid ceramic conductors: it has a linear Arrhenius behavior and maintains a high conductivity at low temperatures. In contrast, most other polymer solid electrolytes and liquid electrolytes have a drastic reduction in conductivity below the glass transition (or freezing) temperature. Furthermore, our coating is stable in contact with a low temperature electrolyte during repeated cycling.

Status: Starting an SBIR Phase II project to develop our artificial SEI and test coin cells and pouch cells: planning to partner with battery producers for larger cells in Phase II. Conducting planning for a tech demonstration.

Acknowledgments:

NASA SBIR Phase I Contract No 80NSSC23CA158

References:

[1] Holoubek *et al. ACS Energy Lett.* 2020, 5, 5, 1438-1447.
[2] US Pat. No. 7,931,824
[3] Additional patents pending

LUNAR FIDUCIAL POINTS: ANCHORING THE LUNAR REFERENCE FRAME ON THE MOON

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Introduction: The Artemis era will depend on the development of systems, such as the proposed LunaNet [1], for the accurate delivery of positioning, navigation and timing (PNT) information on the lunar surface and in cislunar space. These systems will themselves depend on the accuracy of ties between the Lunar Reference System (LRS) and the International Celestial Reference Frame (ICRF), and also on the ability to base PNT updates on sites with known positions and timing (geodetic "fiducial points"). Fiducial points on the surface of the Moon should be very stable; the Moon is dynamically much quieter than the Earth, with no atmosphere or oceans to perturb its rotation. Lunar surface fiducial points will thus be essential for the maintenance of the LRS, and also for the geodetic monitoring of orbital, rotational and tectonic motions of the lunar surface. Here, we describe how fiducial points can be monitored at the few mm level with monthly solutions using collocated Lunar Laser Ranging (LLR) retroreflectors and Very Long Baseline Interferometry (VLBI) radio beacons. Combinations of LLR and VLBI data could usefully determine the $\sim$38 mm yr^{-1} orbital recession of the Moon [2] on a monthly basis, enabling the study of the interaction of this recession with terrestrial tides, climate cycles, and climate change.

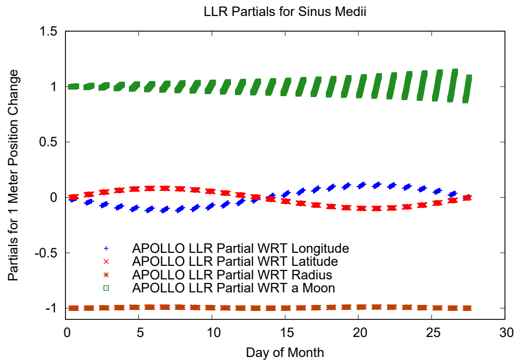

Figure 1: LLR partials for a fiducial point at the center of the near side in Sinus Medii (for the Apache Point APOLLO LLR system). The correlations between the semimajor axis and the radial term of lunar position, and also between latitude and longitude, are evident here, and in the formal errors presented in Table 1.

Enhancing Lunar Geodesy with Collocated Observations: Soon, through CLPS and Artemis landings, the LLR retroreflector network deployed 5 decades ago will finally be extended [3]. In addition, Space Initiatives Inc (SII) is developing COMPASS beacons for the accurate determination of positions on the lunar surface with Very Long Baseline Interferometry (VLBI) [4]. LLR determines the distance of a retroreflector, i.e., its radial position, while VLBI determines the angular position of the radio beacon; simultaneous measurements of collocated reflectors and beacons at a fiducial point can thus determine the position of the point in all three dimensions. Simulated solutions with either LLR or VLBI alone, as in Table 1, consistently show, even for monthly observing campaigns, highly correlated position components with relatively large formal errors for both measurement types. As is indicated in Figure 1, the geometric limits of each measurement type alone can be broken by a combination of the two data types.

Solution	σ_{R}	σ_{θ}	σ_{ϕ}	σ_{a}
Sinus Medii (1 month)				
LLR Only	12.6	57.1	69.3	12.1
VLBI Only	238.8	33.6	29.1	6.3
LLR + VLBI	3.6	16.1	19.4	3.42
Malapert Mt. (1 month)				
LLR Only	87.1	71.3	10.0	13.7
VLBI Only	33.5	32.7	240.7	6.4
LLR + VLBI	20.0	16.4	2.7	3.5

Table 1: LLR, VLBI and combined monthly solution formal error estimates (in mm) for a fiducial site at center of the near Side, in Sinus Medii, versus a fiducial site near the lunar South Pole, on Malapert Mountain (assumed to have continual Earth visibility). At both sites the combined data set breaks the high correlations found with either VLBI or LLR data alone, allowing for a good determination of these parameters.

We conclude that combined solutions using LLR and VLBI data break the geometrical dilution of precision which otherwise hinders short duration determinations of station positions. The combination of LLR and VLBI data from fiducial points with collocated retroreflectors and beacons will significantly enhance the monitoring of station positions, the maintenance of the LRS, and the determination of the recession of the lunar orbit and the free lunar librations.

References:

[1] N. SCAN (2022) Draft LunaNet Interoperability Specification *Tech. Rep. LN-IS V004* National Aeronautics and Space Administration. [2] J. G. Williams, et al. (2016) *Celestial Mechanics and Dynamical Astronomy* 126(1-3):89 `doi`. [3] V. Viswanathan, et al. (2021) in *Bulletin of the American Astronomical Society* vol. 53 134 `doi.arXiv:2008.09584`. [4] T. M. Eubanks (2020) `arXiv:2005.09642`.

RINGSIDE SEATS: LANDER SUPPORT WITH MOTE PENETRATORS

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Introduction: Landing on the Moon is intrinsically difficult, and is made more difficult by the present lack of any local support for landing operations, or any sort of global-positioning system for guidance. Four of the last five attempted lunar landings, have all failed, all apparently because of various software or sensor problems. The Space Initiatives Inc (SII) Ringside Seats™lander support system is based on the SII Mote System developed to provide situational awareness and scientific data from the lunar surface. Ringside Seats packages together already developed Motes, Pankin boxes and COMPASS navigation beacons [1] to provide a support system to reduce the risks of the lunar landing process, provide state information during the landing and an independent source of data on landing problems, and also provide a post-landing PNT and communications network. In case of a failure, Ringside Seats can provide an independent source of data, such as imagery, for forensics.

Probes to Extend Surface Exploration: Space Initiatives Inc (SII) has been developing a set of small probes and drones [2, 3], including Mote™penetrators, Eagle™rocket drones, and Panko™"breadcrumbs." Mote ballistic penetrators can be deployed from descending lander, allowing for small swarms to be set up across a target of interest (Figure 2), offering an economical way to study and instrument a large number of sites in a lunar traverse [3].

Mote™Ballistic Penetrators (see Figure 1) are 360 mm long by 50 mm diameter and feature a hardened steel nosecone with a composite body; an electronics package with power management, data acquisition and storage, flight instrumentation including accelerometers and gyroscopes, and mesh-network RF transceivers; a precise clock source; and on-board power sufficient for operation through one lunar day (more if photovoltaics are carried on the antenna mast). While the penetrator body with its instruments burrows through the regolith, coming to a rest up up to one meter below the surface, the tail section remains near the surface and deploys an antenna mast.

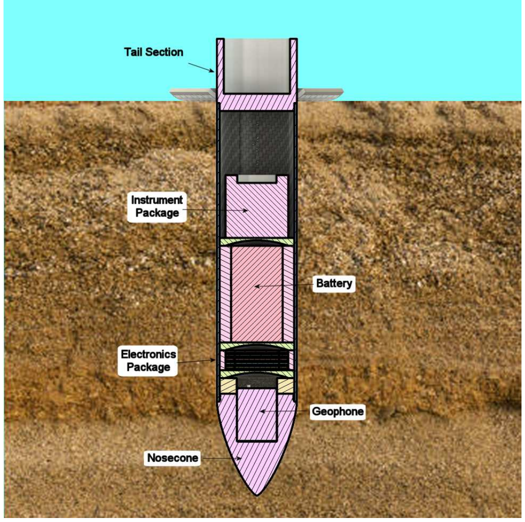

Figure 1: A cut-away image of a Mote penetrator after deployment into the lunar regolith.

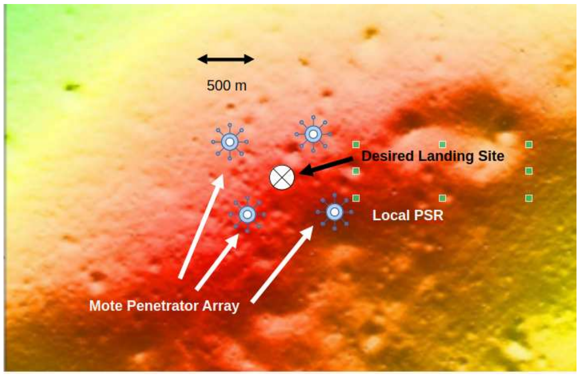

Figure 2: Mote penetrator deployment along the Connecting Ridge (CR1) near the lunar South pole.

Lander Support with Ringside Seats: Figure 2 shows how a string of 4 Motes can be deployed over a region, the Connecting Ridge (CR1) between Shackleton and Gerlach Craters, providing both geotechnic information about the surface and a seismic network to monitor subsurface activity at the site. Each Mote deployment will also automatically set up a mesh communication network for low bit-rate communications back to the lander or rover hub used by the astronauts In addition, Motes can deploy COMPASS beacons (or other radio communications systems) for low-bit-rate communications with Earth, or a relay satellite, in case of a lander failure.

References: [1] T. M. Eubanks (2020) `arXiv:2005.09642`. [2] C. J. Ahrens, et al. (2021) *The Planetary Science Journal* 2(1):38 `doi`. [3] T. M. Eubanks, et al. (2021) in *2021 Annual Meeting of the Lunar Exploration Analysis Group* vol. 2635 of *LPI Contributions* 5036.

Regulatory Challenges and Policy Uncertainties for Government and Commercial Space Nuclear Systems. A. J. Fallgren[1], D. J. Rhodes[1], J. C. Kennedy[1], B. T. Rearden[1], M. Dudek[1, 1]X Energy LLC, 801 Thompson Ave., Rockville, MD, 20852. (Contact: afallgren@x-energy.com)

Introduction: The pathway to a commercial space nuclear industry faces numerous regulatory challenges and policy uncertainties. These challenges and uncertainties are relevant to all space nuclear programs, including Fission Surface Power (FSP), Nuclear Thermal Propulsion (NTP) and Nuclear Electric Propulsion (NEP), and are thus relevant to lunar surface infrastructure development, cislunar activity, and extensibility to Mars. Nuclear power in space is impacted by international treaties [1], international norms [2][3], US Government regulations [4], and US domestic and international policy [5][6][7][8], making it complicated to navigate. We offer a tutorial of this topic, highlighting issues that need to be resolved to lay the groundwork for near term government sponsored projects and long-term commercial activity.

Regulatory Challenges: We divide the regulatory challenges into four categories;

System Components: The regulatory challenges start at the selection and development of the system components. Codes, certifications, and maturity of materials dictate the feasibility of using advanced fuels, moderators and reflectors. These regulations come from industry standards as well as government oversight. Some examples are: licensing of fuel fabrication facilities (NRC), safe transportation of hazardous materials (DOT), sources of High Assay Low Enriched Uranium (Department of State), and safe handling and certification of advanced moderator/reflector materials (metal hydrides, beryllium, etc.).

System Ground Testing: Any developed government or commercial space nuclear system will require some level of ground testing. With the release of NSPM-20, the authority for launch of any LEU/HALEU system has been assigned to the government agency sponsoring the launch. Ground testing oversight would be under the same sponsoring agency. Currently NASA, DOD, and the Department of Commerce have been formalizing the requirements they will have for approving launches. Each of these however will have their own ground test requirements, so that approval of one agency would not guarantee approval by the others should the technology be adapted to a separate program.

Launch: The regulatory hurdles for launch, especially for a commercial system, revolve around indemnification. The Price-Anderson Act lays out how terrestrial nuclear reactors, their operating entities, and the federal government share fiscal risk for an accident of an operating nuclear reactor. It is predicated upon a formal licensing procedure and accepted licensing authorities. Without a similar bounding of financial risk for launch of a space nuclear system, establishing a commercial space nuclear industry will be extremely difficult.

Concept of Operations (ConOps): Once launched the regulations surrounding the operation of a space reactor are largely non-existent. Where a space reactor will be allowed to operate, for how long, with what level of radiation shielding and in what manner are still largely undefined. Currently these decisions would be the responsibility of the nation of origin, posing a risk of international conflicts around usage, operation, and decommissioning of reactors in space.

Policy Uncertainties: Development of a commercial space nuclear industry also faces policy uncertainties. The current regulations currently fall almost entirely under the authority of politically appointed individuals. A change in administration could completely change the regulations. This will prove a challenge for a system that will take multiple years to design, build, test, and fly. Even without the regulations directly changing, the availability of the necessary resources to test and assemble a space reactor is largely dependent upon policy focus. The commercial crew program, and commercial supply missions to the international space station as policy initiatives along with other programs have led to the development of a thriving commercial space launch economy. A similar model could be used to spur the space nuclear industry.

References: [1] Treaty on the Principles Governing the Activities of States in the Exploration and Use of Outer Space, Including the Moon and Other Celestial Bodies (1967). [2] United Nations Principles Relevant to the Use of Nuclear Power Sources in Outer Space (1992). [3] IAEA Safety Framework for Nuclear Power Systems. [4] 100th Congress (1988). HR1414 – Price-Anderson Amendments Act of 1988. [5] IAEA-1197 Nuclear Power in Peaceful Space Exploration. [6] National Security Presidential Memorandum 20 (NSPM-20). [7] Space Policy Directive 6 on the National Strategy for Space Nuclear Power and Propulsion (SPD-6). [8] Artemis Accords.

Searching for Subsurface Shelter: Navigation Planning for Micro-Rover Exploration of Lunar Pits

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Introduction: Lunar pits are unique portals to the lunar subsurface, where long-term human habitats could be established and protected from the radiation, micrometeorite, and thermal hazards of the Moon's surface. To-date, hundreds of lunar pits have been discovered from orbit, but orbital imagery is insufficient to find subsurface habitat.

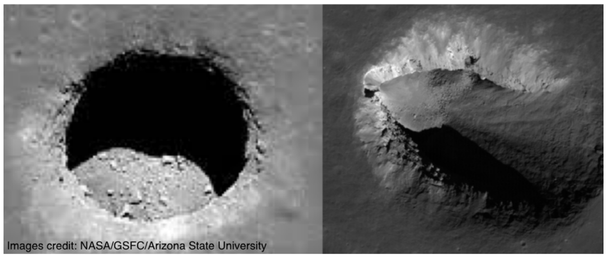

Fig 1. Lunar pits may provide access to sheltered overhangs and cave entrances that could protect long-term lunar habitats.

Small, fast, autonomous microrovers have been proposed to navigate lunar pit rims, image pit interiors, and construct accurate 3D models of the pit morphology [1]. This could be achieved in the near term at low cost with a NASA PRISM-class mission. The High Dynamic Range imaging and 3D modeling required for this ambitious proposal have been developed and evaluated in [2,3,4], but the identification of safe imaging vantage points with wide, overlapping coverage and the development of safe micro-rover navigation routes to attain those vantages remains unexamined. This research addresses those gaps.

Fig 2. Microrovers like this CMU prototype could explore lunar pit rims to discover caves and map safe descent routes.

Vantage Identification and Selection: Working from best-available orbital terrain maps, the algorithm identifies vantage points on the pit rim with wide, overlapping, fronto-parallel views of the pit's interior surfaces. Vantages that cannot be reached without exceeding the micro-rover's maximum pitch and roll limitations are excluded, as are vantages that lie beyond the line-of-sight of the lander's surface communications radio. The final subset of viewing vantages are selected using a greedy heuristic that prioritizes fast acquisition of wide overlapping view coverage.

Navigation Planning: Next the algorithm rapidly generates safe low-level paths connecting each vantage to all other vantages and the landing site. Paths are generated using a variant of A* with a cost function that prioritizes short paths and minimal terrain slope. Using the path segments planned between imaging vantages, a final global exploration route is constructed using an efficient Traveling Salesman Problem solver to design a least-cost route that begins at the landing site and visits all the identified vantages around the pit rim.

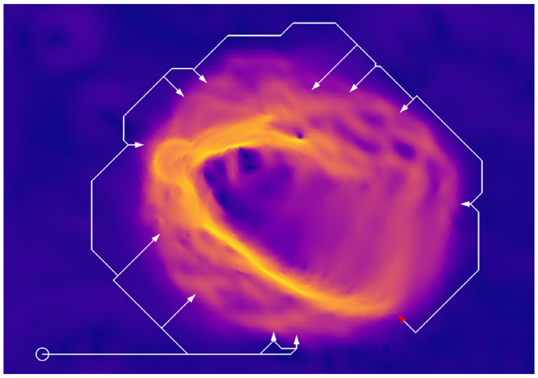

Fig 3. A top-down slope map of the Lacus Mortis Pit with rover exploration route overlaid. The rover departs its landing site (white circle) and visits 12 vantages around the pit rim. At each vantage it images the pit interior and improves its 3D model.

Summary: This work develops efficient algorithms for vantage selection and navigation planning that are needed to enable small rovers to search massive lunar pits for sheltered overhangs and habitable caves. The resulting algorithms are suitable for in-situ planning and replanning to adapt to changing conditions and priorities over the course of a pit exploration mission.

References: [1] Whittaker, W.L., et al. (2021) LPSC, no. 2548, pg. 2644 [2] Ford, J.S. et al. (2021) IEEE AeroConf, pg. 1-7 [3] Ford, J.S. et al. (2021) LPSC, no. 2548, pg. 2631 [4] Ford. J.S. et al. (2020) 3rd PCC, no. 2197, pg. 1062.

Fundamental Regolith Properties, Handling, and Water Capture Project Update. J. Fothergill[1], M. Anderson[1], L. Struchen-Deans[1], and L. Gertsch[2], [1]NASA Glenn Research Center, Cleveland OH, [2] NASA Glenn Research Center/Missouri University of Science and Technology, Rolla MO. (Contact: jenna.fothergill@nasa.gov)

Introduction: Many fundamental problems remain to be solved regarding digging, transporting, and processing lunar and Mars regolith. The capability gaps for producing oxygen (O_2) from lunar regolith, and water from lunar (and Mars) ice, include (among others) how to:

- Dig up hard, frozen icy regolith (ore),
- Transport it to a processing site,
- Lift it into a reactor, and
- Capture the extracted product (water).

All this must be done without losing an excessive fraction of the contained water to the surrounding environment. (What magnitude of loss constitutes "excessive" is outside this study's scope, which is to quantify the effects, thus forming a basis for such decisions.)

To fill some of the open component gaps that are common to multiple technologies for lunar use, the Fundamental Regolith Properties, Handling, and Water Capture (FLEET) project set up a number of small fundamental research studies that involve numerical modeling and physical experiments. This is a summary of the accomplishments and lessons learned to date.

Reducing Excavation Energy: Ultrasonic vibration of the soil-engagement interface of excavation tools is known to reduce digging forces on Earth [1]. Lower forces require lower excavator mass, thus reducing the energy required to excavate a unit volume of ore.

Regolith as a Sealant: The internal cohesion of lunar regolith can withstand a certain amount of pressure differential [2]. This task has evaluated the extent of this property for potential application to sealing regolith transfer points and reaction chambers.

Transporting Ore with Minimal Losses: Some fraction of the target volatiles contained in icy regolith escapes when it is disturbed in the lunar surface environment, beginning when it is dug and continuing while it is hauled from mine to processor and during extraction within the processor itself. The magnitude of this effect during vibration (to simulate ore transport) and heating (to simulate water production) is being evaluated with experiments and numerical models.

Transporting Ore Vertically: Terrestrial industries have evolved various ways to convey granular material upward inside minimal lateral footprints. This task is evaluating variations on a spiral conveyor [3] in a flight test soon.

Growing Ice: Once water has been extracted from regolith, it can be transported in tankers as ice rather than as water. This task looked at the mechanisms by which water vapor can be frozen [4]. Figure 2 illustrates typical agreement of experiment with model.

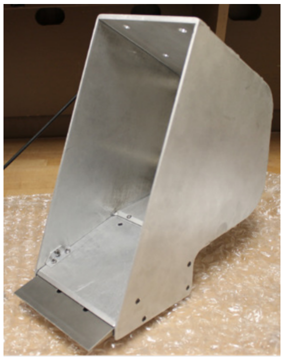

Fig. 1: One of several soil-engagement test articles tested with and without ultrasonic-assist [1].

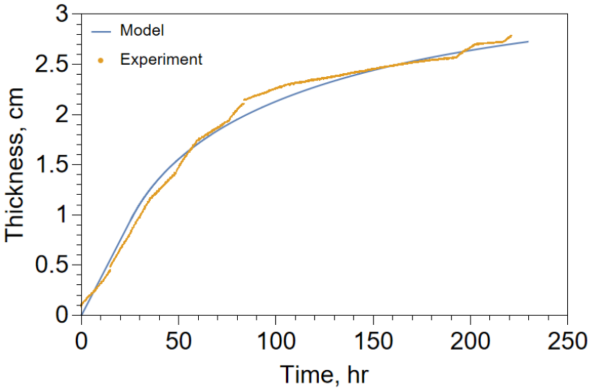

Fig. 2: Measured vs. modeled ice layer thickness from water vapor stream at 500 Pa and 268 K [4].

References:

[1] Rezich E. *et al*. (2021) Earth and Space 2021, 555-563. [2] Stewart, J. (2023) Space Resources Roundtable. [3] Mantovani J.G. *et al*. (2023) Space Resources Roundtable. [4] Krause T.S. *et al*. (2023) ASCEND Conf.

The effect(s) of microgravity on the dormant state of cancer cells.

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Summary: Microgravity exposure could accelerate cancer formation in spacefarers whose bodies harbor dormant cancer cells. To test this possible outcome, relative levels of gene expression (proteins, XNCs or MHCs), cell morphology, proliferation, and intercellular behavior of cancer cells exposed to microgravity on the ISS will be compared to control cells on earth.

Introduction: Despite our increasing success in the early detection and removal of primary cancers, most cancer mortality occurs after periods of remission, during which cancer cells may "hide" from immune and therapeutic detection by entering a period of dormancy [1]. The microenvironmental causes of this period of dormancy, which can last for days, months, or years, are unknown. Also unknown are the physical and chemical signals that trigger re-activation of cancer cell division, eventually leading to tumor formation, metastasis, and death [2]. The few studies that do exist indicate that abnormal levels of certain factors (such as inflammatory, growth, and cell adherence signals) are associated with cancer cell dormancy and proliferation. Disturbingly, several of these factors are co-associated with exposure to microgravity [3]. If exposure to microgravity effects cycles of cancer cell proliferation and/or dormancy, this may impose challenging limitations for future space travel and its long-term consequences. Most directly, microgravity exposure could accelerate cancer formation in spacefarers whose bodies harbor dormant cancer cells. Our team will analyze the effects of a microgravity environment on cultured B3B7 cancer cell lines from the model organism *Xenopus laevis* (African clawed frog). Specifically, we will measure relative levels of gene expression for dormancy-associated proteins, which will be compared between microgravity-exposed cancer cells, and cancer cells not exposed to microgravity.

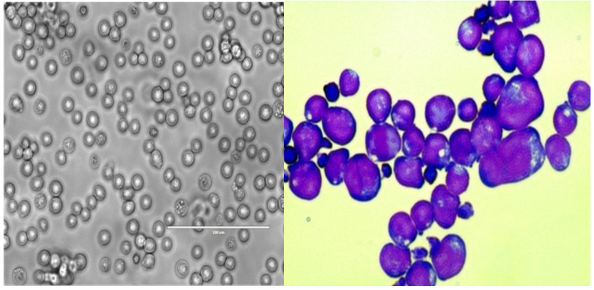

Fig. 1: Proliferating (left) and dormant/proliferative-mix (right) Xenopus B3B7 lymphoma cells.

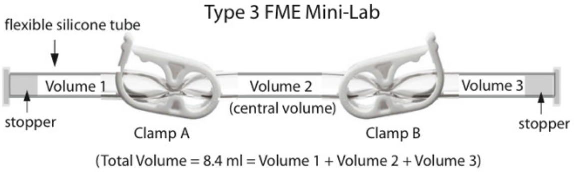

Fig. 2: Experimental enclosure. Cells will be seeded in media in Volumes A and C; fixative in B.

Additionally, cell morphology, proliferation, and intercellular behavior will be assessed in all groups. This study will directly aid in our understanding of microgravity's impact on cancer dormancy and activation, while improving our limited understanding of the phenomenon of cancer dormancy more broadly.

Preliminary Results: In partnership with F. Andino and J. Roger at Syracuse University, we conducted preliminary experiments under simulated conditions on the *Xenopus* cells. We seeded cells at varying concentrations (from 100 to 100,000 cells/mL) and varying temperature conditions (from 4 to 27 degrees Celsius. The ideal seeding concentration identified so far is ~100-1000 cells/mL; the cells exhibit density dependent growth; higher concentrations result in too rapid proliferation. Weeks 3-5 represent the ideal time for cell fixation, as there is a mix of proliferating and dormant cell phenotypes observed. After ~week 5, cell concentration slowly declines, until ~week 8, when concentration decreases dramatically. However, viable cells were still present at experiment conclusion at 9 weeks; raising our confidence that the 'live' chamber will return with viable cells upon return from the ISS for further analyses.

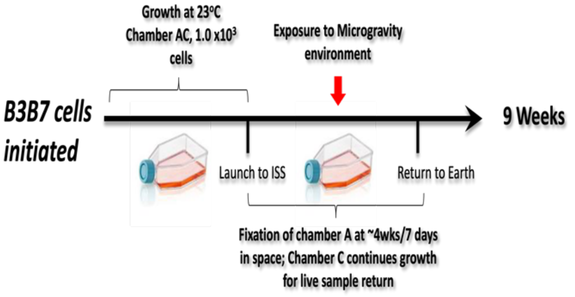

Fig. 3: Experimental timeline to sample return.

References: [1] S.Y. Park, J.S. Nam. (2020). *Exp Mol Med* 52, 569–581 (2020). [2] A. Wells et al. (2018). *Experimental Biology and Medicine 1243-1253*. [3] C. Ludtka, et al. (2021). *Microgravity*, *7*(1), 1-10.

The Power of Lunar Dust: Based on a Triboelectric Generator (TENG) Model.

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Introduction: Lunar landers will contend with their "number one concern", charged dust (a probable cause for descent crashes due to sensor malfunction), such as the Chandrayann-2 (as realized by Surveyor 3 failed surface radar lock). Capacitive reentrant (fractal dimension ≈1.2) lunar dust mitigation is of high importance because the reentrant dust increases the probability of astronaut dust pneumonia, damage, and destruction of surface equipment. Dust is mechanically, solar wind, and Helio-frequency triboelectrically charged. Measured terrestrial wind-blown dust created $180kV$ and Dust Bowl dust storms created lightning that destroyed automobile ignition systems. This infers that lunar landers will experience surface dust ejecta voltages from thousands to millions of volts and is ~25 orders of magnitude higher than charged dust at rest [1].

This White Paper presents a triboelectric nano generator (TENG) using a linear dc-dc slide movement of charged dust that can be projected to a static electricity-enhanced Stokes Number to approximate the number of coulombs (C) of one metric tonne of lunar dust. Fractal agglutinate dust has an overall charge greater than the sum of its parts as elongation, surface roughness, fractal characterization plays a major role in the behavior of particles in flow streams affecting both inertia and drag forces on the particle. Continuous drag forces of sequential contact-detachment of two different particles are the cause of triboelectric nano generation, known as TENG. The electrical power of dust takes two forms, 1) particulate and 2) differing aeolian cloud formations with potentials of hundreds of kilovolts per meter [2], [3]. The engine dust ejecta (i.e., aeolian) lunar electric field is expected to be stronger than terrestrial aeolian electric fields due to charged "electrostatic forces acting upon the grains" [4]. To characterize the engine's ejecta electric field, charge per mass, and power of lunar dust we must determine the electrical equivalent of one agglutinate fractal dust particle.

The charge of alumina particle size 4.5μ (specific gravity ≈3.7) resembles fractal augite containing aluminum and oxides, with a specific gravity of 3.3, an alumina surface area of $\approx 2.95m^2/gram$, a single particle charge of $\approx 5.4x10^{-17}C$, $68.4C/gram$, where:

$$C = Ampres \cdot \text{seconds}$$

This dust electrical circuit form is a generator and resistive load, in parallel, then in series with a variable capacitor. [5], [6].

The approximate charge for augite is $\approx 2.2x10^{-12}C/m^2$. Lunar dust at rest is $\approx 68.4x10^{-7}C/metric\ tonne$.

Dust storms are known to affect the lifting and transport of electrified dust particles.

The space-charge density exhibits a universal three-dimensional mosaic of oppositely charged [cloud] regions, induced by high Reynolds number engine exhaust turbulence. A linear relationship exists between the space-charge densities and dust concentrations. Engine exhaust electrostatic dust forces are expected to lift dust by more than a factor of ten. The electrostatic forces will disperse and attract dust. "A mosaic pattern is attributed to the turbulence-driven separation of the oppositely charged particles." Dust traveling at $\approx 15m/sec$, $7.72mg/m^3$, with $180kV/m$, demonstrated a "strong and highly electrified storm." The dust resting value is $1.6x10^{-19}C$. The observed power values were between $-1\ to\ 1x10^{-2}\mu C/m^2$ and $5.5\ to\ 11kV/m$ [7].

As a lander enters fine braking upon descent, (like the Apollo 11 at $\approx 33m$) wisping dust begins the dust growth stage by increasing its concentration and E-field intensity. The second mature stage, where descent thrust and intensity are at an equilibrium until MECO, resulted in the terrestrially measured $180kV$/m value. (Super charging of the permanent asymmetrical lunar dust clouds with higher concentrations of charged lunar surface dust is highly probable). The third stage is the hovering and deposition of lunar dust, [8].

Triboelectrification of terrestrial dust, first at rest, then windblown, increases 22 orders of coulomb magnitude with measured voltage at $180kV/m$. It is expected that turbulent high velocity engine exhaust blast ejecta will create plumes of mosaic clouds of differing electrical potentials likely inducing significant power into and across lunar surface equipment, exceeding hundreds of kilovolts.

Complete references can be found at https://www.mediafire.com/file_premium/h9fol6ib0my2ofo/The_Power_of_Lunar_Dust_references.pdf/file.

References: [1] Zhang, H., Zhou, YH. (2020). Reconstructing the electrical structure of dust storms from locally observed electric field data. Nat Commun 11, 5072. [2] See note 1. [3] A constant current triboelectric nanogenerator (TENG) arising from electrostatic breakdown - science. (n.d.). https://www.science.org/doi/10.1126/sciadv.aav6437. [4] See note 3. [5] He, X., Zhang, H., Jiang, J., & Liu, X. (2023). Output characteristics of series-parallel triboelectric nanogenerators. Nanotechnology, 34(15), 155403. https://doi.org/10.1088/1361-6528/aca599. [6] Rodrigues, M. V., Marra Jr., W. D., Almeida, R. G., & Coury, J. R. (2006). Measurement of the electrostatic charge in airborne particles: II - particle charge distribution of different aerosols. Brazilian Journal of Chemical Engineering, 23(1), 125–133. https://doi.org/10.1590/s0104-66322006000100014. [7] See note 1. [8] See note 1.

Lunar Infrastructure Construction Using GITAI's Autonomous Robots.

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Introduction: GITAI [1] has been developing high-capable general-purpose robots for space development. As for our space track record, we successfully demonstrated our autonomous robot capability inside the ISS in 2021 [2]. We will also launch our dual robotic arms with task units for in-space technology demonstration this December [3]. In parallel, we have been developing robots to construct lunar bases and infrastructures, exploration[4]. We have been conducting collaborative task demonstrations and have accumulated lessons learned. As our next milestone, we will demonstrate constructing a large tower using our rovers and Inchworm robots described in the following section.

GITAI's Lunar Robots: GITAI's lunar robotic technologies consist of two main robots: Inchworm Robots and Rovers (see Fig. 1).

GITAI's Inchworm robots are one of our main products. This 7-DoF mobile robotic arm has end effectors on each end. Each end effector has a wireless power port and grapple mechanism so the robot can move over wherever the grapple fixture is installed.

GITAI rovers have been updated to increase the payload capacity to mount multiple Inchworm robots and detachable tools. The rover has rocker-link suspension to traverse rough terrain and wheels to drive over loose terrain. With multiple Inchworm robots, the rover will become a mobile multi-arm robot.

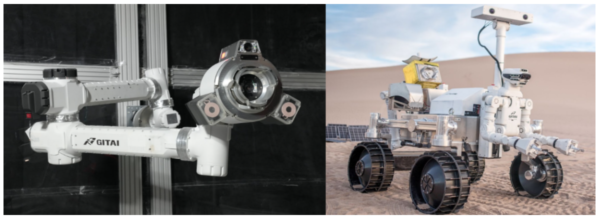

Fig. 1: GITAI's Inchworm robots and rovers. In this field test campaign, we have demonstrated a variety of collaboration tasks by Inchworm robots and rovers.

Towards Lunar Environment: To accomplish lunar construction by autonomous robots, they must survive harsh lunar environments: lunar dust and lunar night survival, and typical space environments, such as high vacuum and radiation. Therefore, our in-house components for all GITAI robots have continuously improved and confirmed to satisfy running in a simulated lunar environment throughout the durability test in regolith simulant bin and cryogenic test using liquid nitrogen. Moreover, the in-space tech demo this December will prove both component/robot-level maturity to be space ready.

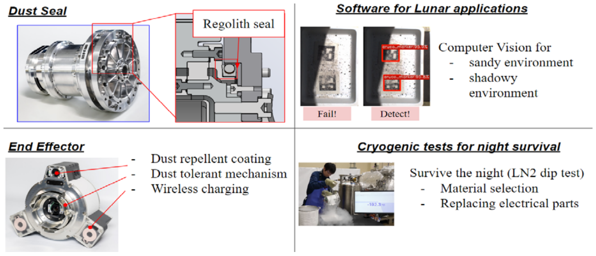

Fig. 2: Implementation of countermeasures for lunar environments on key technologies.

Tower Construction: To achieve lunar infrastructures constructed by robots, robotic systems need to address larger objects than the robot itself at the end. Tower construction is one of the challenging tasks using robots and an important milestone for us because it has a high potential to utilize the technologies to several infrastructures, e.g., communication tower and solar array tower at the south pole. As each tower component became heavy for the rigidity of the tower, we decided to use a crane to hang each tower component and use multiple Inchworm robot arms to adjust, stack, and connect each component securely as shown in Fig. 3.

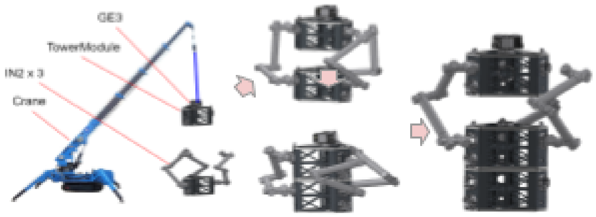

Fig. 3: Tower construction concept using three Inchworm robots with a crane. Each tower module has grapple fixtures, and the crane tip has a GE3 grapple end effector to grasp the module like IN2.

Future Prospects: GITAI will keep improving our autonomous robotic technology. In particular, we will conduct TD-VAC testing this winter to prove that our latest Inchworm robot is lunar-ready.

References: [1] GITAI web page, [2] S1 PR, [3] S2 PR, [4] S. Higa, et al., GITAI r1 rover for lunar exploration and base construction. In 2022 Annual Meeting of the Lunar Exploration Analysis Group, Laurel, Maryland/Virtual, Aug 2022, [5] GITAI Lunar measures 2023.

Advanced Nuclear Powered Closed Brayton Cycle for Space Power Applications.

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Nuclear powered generation systems have been proposed for several space missions, dating back to the 1970's.[1] The closed Brayton cycle (CBC) offers advantages over competitors, including high conversion efficiency, reliability, and scalability from single kilowatts to several megawatts [2]. Past NASA efforts to develop the CBC have focused on moderate temperature thereby lowering risk and development time. Advances in turbomachinery and recuperator design and materials enable an expanded operating temperature range. Reactor developers also foresee future advancements with heat delivery temperatures from current 1100K levels, approaching 1700K in the next 5 years. This paper explores the upper limits for reactor and CBC temperatures, while defending the life targets of >10 years. This information is combined with quantitative mass models for the reactor, heat source heat exchanger, turbomachinery, recuperator, and radiator to predict the minimum system mass for various power levels.

System optimization for mass minimization: The power conversion system mass and volume must match launch vehicle specifications. The subassemblies modeled in this study include the reactor and associated radiation shielding, the radiator, and the CBC. A representative placeholder is provided for the power management and distribution (PMAD) system. While the CBC mass represents the smallest fraction of the mass budget, its performance parameters drive the weight of the reactor and radiator. Mass of the reactor ties to the CBC efficiency while the radiator mass depends on heat rejection temperature, a controlling factor in the engine's efficiency. A model of the system has been created that optimizes the cycle's aerodynamic, thermodynamic, and heat transfer parameters to minimize mass. This model is calibrated over a range of turbine inlet temperatures from 1100K to 1700K, respecting creep life boundaries for the turbine and recuperator. The study derives turbine and compressor aerodynamic efficiencies for a range of power levels, employing best practices computational models and experience. The study concludes that increasing the TIT to 1700K results in nominally 40% decrease in mass as compared to the 1100K TIT baseline.

Realizing these mass savings must be accomplished without compromise to the operational life of the power plant. This study analyses the creep-life in the gas turbine's hot section and recuperator. Conventional microturbine alloys do not have sufficient strength to be used above about 1200K. This paper evaluates conventional turbine alloys, refractory alloys, and ceramics to establish limits for each. Working fluids properties, varying the ratio of He and Xe are shown to have an impact on the temperature threshold of each class of turbine material. Lastly, new gas turbine architectures are considered to minimize pressure losses and maximize reliability.

Recuperator temperatures up to 1330K are studied, considering nickel, nickel-cobalt, and refractory alloys. The recuperator architecture analyzed conforms to a proven gas turbine and microturbine design which has successfully operated in the field for over 20 years, accumulating many millions of operating hours. The recuperator, manufactured by Brayton Energy, will be optimized for the new CBC specification for minimum mass and creep life over 100,000 hours. The aforementioned system mass minimization model explores thermal effectiveness over a wide range, up to a limit of about 97% and pressure losses from 1 to 4% in each circuit.

The closed Brayton cycle operates with only one rotating part floating on gas bearings with non-contacting seals. Each component in the gas turbine engine has been analyzed for 10, 25, and 500 kWe case studies. This covers a wide range of future NASA and US Air Force platforms. Building upon the substantial historical work by NASA and their contractors, one of these Brayton power plants can be ready for launch before the end of the decade.

References:

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[2] M. Lee, "Comparison of Energy Conversion Technologies for Space Nuclear Power Systems," 2019, Accessed: May 02, 2023.

Thermal Technologies for Lunar Ice Extraction & Collection.

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Introduction: Advanced Cooling Technologies, Inc. (ACT) in collaboration with Honeybee Robotics is developing a Thermal Management System (TMS) for lunar ice mining. The TMS consists of two principal technologies: a) Thermal corer for ice (or volatile) extraction and; b) cold trap tank for ice (or volatile) collection.

Thermal Corer: Ice extraction performance of two thermal corer prototypes: 17.3 cm long made with stainless steel and 34.5 cm long made with aluminum alloy is presented here. The inner diameter of the thermal corer is 5 cm. About 60-70% ice extraction efficiency was achieved with the 17.3 cm long thermal corer. ACT is currently characterizing the ice extraction performance of the 34.5 cm long thermal corer. Figure 1 shows the prototype thermal corers tested for ice extraction.

Figure 1. Thermal corer prototypes for ice extraction. Left: 17.3 cm long stainless steel based thermal corer; Right: 34.5 cm long aluminum alloy based thermal corer

Cold trap tank: The extracted volatile vapors must be collected in a cold trap tank which is at a very low pressure and temperature. These thermal conditions result in the volatile converting back into solid form on the collection surface. To facilitate efficient ice collection, ACT is developing a Variable Conductance Heat Pipe (VCHP) based cold trap tank. The VCHPs are a form of heat pipes which allow modulating the heat transfer rate and thus the ice collection in the tank. The heat pipes operate normally removing heat from the vapor and rejecting it to deep space through the radiator panels. When the ice thickness is sufficiently high and the ice deposition rate decreases, the ice can be melted into a pool and collected at the bottom of the tank by removing access to the radiator panels by pushing the non-condensable gas front into the heat pipe condenser section connected to the radiator. Figure 2 shows the assembled VCHP cold trap tank.

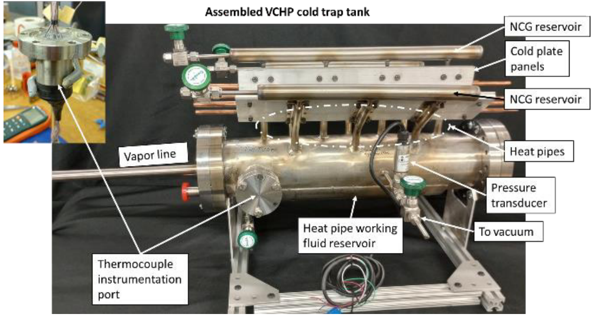

Figure 2. VCHP cold trap tank for ice collection

References: [1] K.L.Lee et al., Waste Heat-based Thermal Corer for Lunar Ice Extraction, *51st Int. Conf. Env. Systems*, 2022; [2] K.L. Lee et al., Demonstration of ice-extraction and ice-collection system for lunar ice miners, *52nd Int. Conf. Env. Systems*, 2023.

PLUMMRS: A Collection of Plan Ledgers and Unified Maps for Multi-Robot Safety

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Introduction: As space exploration missions move farther from Earth for longer periods of time, outposts such as the Gateway will play a crucial role in providing essential support for long-term human presence on the lunar surface as well as serving as staging points for deep space exploration. In the absence of a permanent crew, robots will be expected to perform maintenance and caretaking tasks with limited human supervision. For this purpose, we postulate that heterogeneous robots will benefit of possessing information sharing capabilities that provide them with the spatial awareness necessary for them to work together in a safe, efficient and cooperative manner. In this abstract, we present a collection of software processes named PLUMMRS (A Collection of Plan Ledgers and Unified Maps for Multi-Robot Safety), which consists on 3 modules that allow robots to share information about the environment, their own internal states and expected future behavior. These modules allow independently-developed heterogeneous robots to work with and around each other in a safe manner, as well as providing tools for cooperative operation.

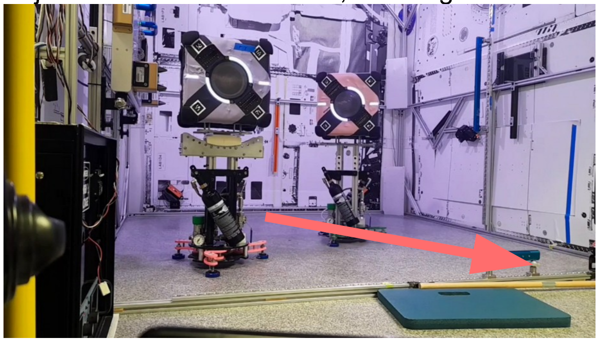
Description: PLUMMRS[1] consists on a set of 3 software modules that allow the robots to store, retrieve and (indirectly) share information among them by means of accessing the centralized PLUMMRS modules. PLUMMRS is built as a set of ROS1 nodes that run in a ground machine, thus not requiring the individual robots to run additional software. These 3 modules are:

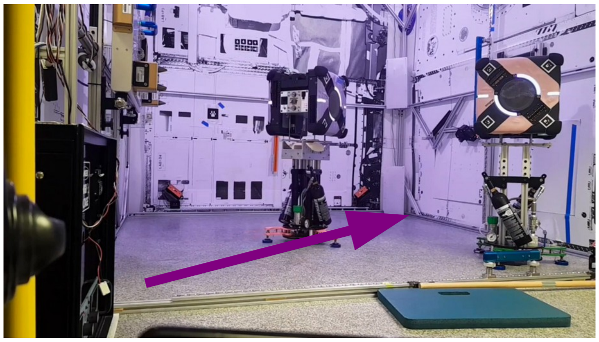
Unified Representation (UR): This module stores the spatial information of the environment, the current location and configuration of the robots. Additionally, this module is capable of storing a variety of task-dependent information, such as 6D inspection poses, annotated RGB images, object semantic information and robot action descriptions. The UR is implemented using a plugin based architecture that allows for easy extension to support new types of user-defined data.

Plan Ledger (PL): This module stores the robots' motion trajectories and whether they are being executed. The PL offers services that allow robots to register their intended plans and status.

Safety Monitor: This module runs at a high frequency (100Hz) to constantly check that safety conditions are being met. Two types of checks are performed: (1) Robots currently moving along a trajectory are following their motion plan (no drifting), and (2) Robots in motion do not have future collisions along their expected trajectories with other robots (also in motion) .

Experiments: We performed tests of these modules using 2 simulated Astrobees operating in a ISS-like environment as well as in real freeflyers at the Granite Lab at the Ames Research Center. The robots were able to move across intersecting trajectories in a safe manner, avoiding collision.





Acknowledgments: This work is supported as part of the NASA SBIR program (award 80NSSC21C0493). The authors thank the Astrobee team at ARC for their technical help.

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Designing Lunar Position, Navigation, Timing, and Communications Systems with GPS Time-Transfer. K. Iiyama[1], A. Sanchez[1], G. Casadesus Vila[1], M. Cortinovis[1], T. Mina[1], and G. Gao[1], [1]Stanford University, William F. Durand Building, 496 Lomita Mall, Stanford, CA, 94305 (Contact: gracegao@stanford.edu)

Introduction: Establishing a sustained human presence in the lunar environment necessitates precise Position, Navigation, Timing (PNT), and communication services. State-of-the-art, vision-based navigation techniques are sensitive to lunar lighting conditions and require users to maintain a high-fidelity map. Additionally, traditional communications rely extensively on the Deep Space Network for data transfer, which services users individually and is limited in scalability [1]. With many planned lunar missions, NASA and ESA have put forth plans for a SmallSat-based PNT and communication architecture. A dedicated Lunar Navigation and Communication Satellite System (LNCSS) would allow for autonomous operations without continuous interaction with Earth-based teams, and enhance overall real-time position accuracy [2]. Moreover, NASA has selected Nokia to develop an LTE communications network on the Moon, which requires precise time synchronization. Both LNCSS and LTE networks must be compact and resource-resilient due to limited SmallSat payload capacity, ground monitoring resources, and ease of transportation and scalability in the lunar environment [3]. We develop precise, robust, scalable, and low-Size Weight and Power (SWaP) technologies for PNT and communications to support sustained human presence on the Moon via the following research fronts:

1. Time-Transfer from GPS for Lunar Navigation and Communications: Lunar PNT and communication systems require precise time synchronization while satisfying stringent SWaP requirements. We leverage existing terrestrial GPS infrastructure for time synchronization in the lunar regime, decreasing the development and operational cost of these lunar systems. We propose timing filters to update onboard clock bias and drift rate with time transfer from intermittent GPS signals [4]. We validate our approach via simulation for a lunar satellite and a network of lunar communications stations. We demonstrate user range errors on the order of 10 meters in orbit using low-SWaP onboard clocks. We further demonstrate robustness to varying transmission delay errors for surface communications [4,5].

2. Terrestrial GPS Time Differencing Carrier Phase Positioning and Timekeeping: Extending our prior work, we propose a positioning and timekeeping technique that utilizes millimeter-level accurate carrier phase measurements from GPS signals [7]. We fuse pseudorange, time-differenced carrier phase, and internal measurements via an augmented state filter. We test this technique for an LNCSS satellite and a lunar rover, achieving meter-level positioning performance compliant with NASA service requirements [6,7].

3. LNCSS System and Ephemeris Design: Beyond designing low-SWaP time synchronization strategies, we study other design choices for the LNCSS. We examine constellation configurations with GPS time transfer to support operations at the lunar South Pole, trading off navigation, communication, and satellite systems factors to meet internationally established requirements for an LNCSS [8]. We further study the parameterization of LNCSS satellite ephemeris, demonstrating the ability of coordinate-based parameterization capability to approximate ephemeris in diverse orbits and abide by NASA service requirements [9].

4. High-Fidelity Environment Modeling: The precise PNT solutions outlined prior require accurate modeling and simulation of the lunar environment. We propose a novel framework to provide onboard relativistic timing corrections for signal transfer between a satellite and a lunar user [10]. We also model a reference geoid of the South Pole to facilitate navigation in this region [11]. Finally, we are developing an open-source LNCSS simulator capable of modeling complex spacecraft dynamics, communication networks, and onboard software execution. These frameworks are essential to integrate and compare novel PNT and communication algorithms for lunar users [12].

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Resilient Lunar Infrastructure Requires Lunar Dust Resilience. K. K. John[1,2], A. M. Fritz[1], and B. E. Troutman[1], [1]NASA Johnson Space Center, [2]NASA STMD.

Introduction: As we get one step closer to more steps on the lunar surface, and even closer to commercial landers and payloads on the lunar surface, the need for dust mitigation is imminent. A resilient lunar infrastructure will require lunar dust resilience.

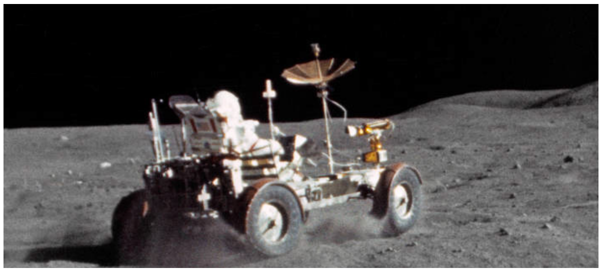
Updates for Dust Mitigation at NASA: NASA's Space Technology Mission Directorate (STMD) has recently announced three significant technology developments in the world of dust mitigation through STMD's Small Business Innovation Research (SBIR) Sequential Phase II and STMD's Lunar Surface Technology Research (LuSTR) programs. SBIR includes opportunities for small business technology development through the "Dust Mitigation and Extreme Lunar Environment Mitigation Technologies" topic. As NASA's Exploration Systems Development Mission Directorate (ESDMD) prepares for the lunar surface, there have been several dust mitigation technology efforts initiated. Additionally, multiple NASA programs are creating higher fidelity dust mitigation strategies. Additionally, NASA STMD is releasing a dust mitigation best practices guidebook. Additional guidance on dust deposition techniques and dust mitigation coating compatibility guidelines are also in work to share with industry and academia. The recent Lunar Surface Innovation Consortium (LSIC) Lunar Proving Grounds Definition Workshop highlighted the considerations for facilities and testing needs [1]. This is relevant to all six LSIC focus areas, with dust mitigation being central to several conversations around lunar proving grounds.

Lunar Surface Data: Commercial landers as well as payloads from industry, academia, and NASA prepare for upcoming trips to the surface of the Moon via the Commercial Lunar Payload Services (CLPS) initiative. The NASA and LSIC Dust Mitigation teams are working to capture engineering data needs from these missions that are relevant to dust mitigation. The goal is to engage closely with academia and industry in Spring 2024 to capture these needs.

Lunar Dust Resilience: As we move to a lunar economy that includes sustainable infrastructure, the words "dust mitigation' and "resilient infrastructure" go hand in hand. From rovers that need to remain mobile for years to solar panels that need to remain highly efficient despite the extreme environment of the Moon, it is essential that dust mitigation solutions are considered. From individual components (e.g. rotary bearings) to systems (e.g. rovers) to capability areas (e.g. excavation and construction), dust mitigation will play a role. NASA, industry, academia, and international partners are all contributing to active and passive technology solutions, as well as architectural and operational solutions.

Dust Mitigation Swimlanes: As NASA engages more and more with partners on dust mitigation technology development and dust mitigation strategies, there are four areas (or swimlanes) used to capture our progressive strategy. These four swimlanes include dust measurements, passive dust solutions, active dust solutions, and dust tolerant components. Dust tolerant mechanisms was highlighted at last year's LSIC Fall Meeting [2].

Next Steps: More information about updates from NASA STMD and ESDMD will be showcased at the LSIC Path to Sustainable Technologies in the Lunar Surface Environment virtual workshop in November [3]. This workshop will highlight existing standards and facilities, stakeholder needs, and a **call to action** for the community. To truly enable a resilient lunar infrastructure in the extreme environment of the Moon, dust mitigation is imperative.



The Apollo Lunar Roving Vehicle (LRV); Credit (NASA)

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Near-Term Policy Considerations for Lunar Missions. Therese Jones[1], Gabriel Swiney,[1] and Katie McBrayer,[2] [1]NASA HQ, 300 Hidden Figures Way SW, Washington, D.C. 20546, [2]NASA Langley Research Center, 1 NASA Drive, Hampton, VA, 23666. (Contact: therese.m.jones@nasa.gov)

Introduction: More than two dozen lunar missions are planned prior to the Artemis III crewed lunar landing, from Russian, Chinese, Indian, Japanese and U.S. government orbiters and landers to Commercial Lunar Payload Services missions to commercial crewed flybys. While the Artemis Accords have established an international consortium of countries seeking to mitigate interference between operations on the Moon, a number of unaddressed policy issues remain that may be critical to lunar operations. In this lightning talk, we build upon NASA's Office of Technology, Policy, and Strategy's September 2022 Report "Lunar Landing and Operations Policy Analysis" [1], to give an overview of policy questions that remain open, including: whether to prioritize certain landing locations or avoid certain scientifically valuable locations, design and coordination of safety zones, notification of other actors of potential dangers posed by landing, whether to avoid placing equipment in operationally valuable locations, and end-of-life disposal. We will also discuss how these policy implications could apply to planned missions.

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Translating learning to and from the resources sector

Michelle Keegan[1], [1]AROSE, 191 St Georges Tce, Perth WA 6000. (Contact: michelle.keegan@arose.org.au)

Introduction: Driven by the very near term time horizons set by the space sector to create a sustained lunar presence, combined with the increasing complexity and urgency in discovering and operating new critical minerals operations on earth, there is a significant opportunity and need to rapidly learn from each other. The design of a sustainable lunar and next generation sustainable earth architecture are urgent goals by both. With a natural angle for collaboration between companies in the space sector and an accelerated propensity in the resources sector now, the cultural requirements are present. The establishment of a resources consortium is seen as the catalyst to accelerate action between the resources industry and LSIC (and ultimately NASA). This consortium would hold sufficient expertise, combined with a very clear articulation of future design needs, in order to bring to the space industry to define or contribute to the required parameters and constraints of a lunar architecture. This would be possible with a quid pro-quo expectation.

Technology and design transfer opportunities: Areas of transfer to the resources sector that are of interest can be simply categorized as either exploration or extraction.

Exploration

In the resources sector, we traditionally require large amounts of material to be analysed, in order to reduce uncertainty and characterize an orebody. While in addition we work to time lines that do not take into account for the ubiquitious communications systems now in place, as well as the increased analysis capability. We expect that we bring an extensive set of experiences required to map and define a resource, but can accelerate whats possible from space via miniaturization and taking mission driven approaches.

Extraction

The resources sector have long applied large numbers of robots at scale, into operations moving over 2 B tonnes of material per annum alone in Western Australia, while interacting with humans onsite and offsite. However the challenges in and around communities and operations are driving new parameters and constraints to work to.

The next generation sustainable earth architecture requires operating with limited water, energy, people and footprint to achieve a sustainable mine with an improved recovery of the orebody at zero emissions.

The resources industry is looking to the space sector to learn how to run dry processing plants, how to design processing plants to run with intermittent energy constraints, how to re-design the mine architecture to account for multiple new processes to account for leaving a zero footprint outcome. Under these new constraints, new architectures are being solved for and built. The opportunity is to design these more rapidly, to help bring new operations into existence faster. Working within the mining and METs sector alone will not achieve a leap frog in design or innovation at the required speed.

There is a desire for two way transfer.

Next steps: The Australian mining industry are known as the pioneers of automated operations in remote regions. As such, a resources community from this region makes logical sense to establish a connection to LSIC.

Redesign of the surface architecture

Defining the parameters and constraints of the architecture required to support a sustained presence on the lunar surface can be achieved while redesigning the new architecture required on earh.

A formal call to industry should be made by LSIC for the creation of a resources consortium. This could be done in conjunction with the Australian Space Agency or by another body.

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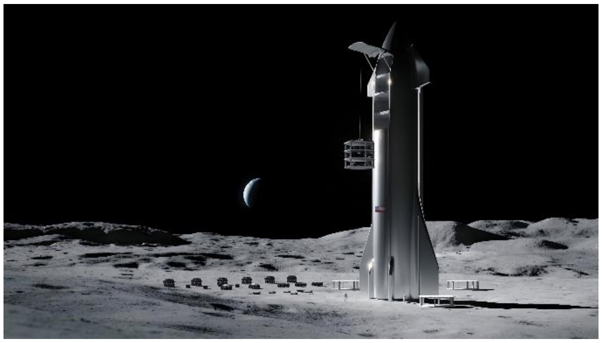
BUILDING A SOLAR SYSTEM CIVILIZATION – HOW OFFWORLD'S TERRESTRIAL SWARM ROBOTIC MINING AND CONSTRUCTION ROBOTS WILL OPERATE ON EARTH AND THE MOON.

J. Keravala, K. Acierno, G. Wasilewski, C. Leavitt, M. Nall, K. Mosavat, D. Isaac

Introduction: OffWorld is building millions of smart robots working on the human supervision on earth and in space, turning the solar system into a habitable place for life and civilization. Enabling human expansion off our home planet is the most important objective of our civilization, for three reasons:

- species level life insurance policy
- sustainable development on earth,
- opening up the new frontier.

Mission: What we absolutely require in space is a robotic workforce for tough jobs. We need to be able to excavate underground habitats and extract water ice and materials. From the collective volatile's we need to make drinkable water, breathable air and rocket propellant. In order to sustain expansion we need to be able to manufacture basic structures and solar cells so that we can produce unlimited power. Ultimately, these systems will need to replicate themselves for rapid and economic expansion. In order to do this, we need to emulate the entire infrastructure value chain from mining, processing, fabrication, assembly and construction. However, we cannot just export current Earth-based practices and technology. We must reinvent how we undertake these processes here on earth, and transfer them directly to the expansion of civilization into the solar system.



Program: OffWorld has undertaken extensive Research and Development in the field of extreme environment industrial robotics initially applied to the mining and processing sector. The objective is the establishment of an end-to-end collaborative robotic system comprising of hundreds or thousands of multi-species robots working together with internal and collective autonomy to achieve strategic objectives.

With the ongoing input of mining industry expertise on a daily basis, OffWorld has developed its robotic systems hand in hand with leading edge knowhow from the mining sector. Initially, we developed baseline systems analysis tools for modelling a variety of scenarios with our robotic architecture, including rapidly deploying them for space-based operations.

Key to the future of operations in space is the ability for robotic systems to undertake multiple complex tasks autonomously and with minimal human intervention. OffWorld has been developing a task agnostic machine learning framework to address and optimize any industrial process. This revolutionary approach to minimally supervised autonomy ushers in a new era of remote operations in extreme environments such as the Lunar or Martian surface. We are already developing the first suite of machine learning agents.

OffWorld is currently developing icy regolith processing to gaseous oxygen and gaseous hydrogen subsystems using four distinct processes: 1) Lunar Excavation System, 2) Volatiles Extraction Subsystem, 3) Volatiles Separation and Preconditioning Subsystem, and 4) Water Electrolysis Subsystem, capable of developing a suite of products from crude water to propellant, as well as byproducts like hot desiccated regolith. Each process is envisioned as a function within an autonomous robotic platform. Our ISRU Technology subsystem is a subset of OffWorld's overall concept for mining Moon and Mars regolith for volatiles and minerals in addition to processing, manufacturing and construction robots within the same robotic platform.

Our subsequent goals in near-Earth space for the expansion of this modular toolkit are to enable the formation of multiple terrestrial and lunar mining species of robots that can be subsequently reapplied to multiple sectors. Once our machine intelligent robotic system has mastered lunar surface and in-space operations, we will expand their utility to near Earth asteroids and the Martian surface, leveraging lessons learned to enable the expansion of humanity into the solar system.

Laboratory study of the geophysical and spectral properties of icy lunar regolith for water exploration and excavation.

T. Kim[1], L. Griffiths[1], B. A. Lange[1], D. Alves de Silva[1], S. Quinteros[1] and T. D. Mikesell[1], [1]Norwegian Geotechnical Institute (NGI), (Contact: luke.griffiths@ngi.no)

Introduction: The future of human development on the Moon depends on our ability to extract water from ice at the lunar near-surface. Whilst water ice has been discovered within permanently shadowed craters in the lunar polar regions, its exact spatial distribution in terms of depth and concentration remains unclear. With the lunar south pole being the target for upcoming lunar lander missions, there is a current need to better understand the composition and quantity of the icy regolith.

On Earth, geophysical and remote sensing methods are commonly used to map subsurface resources (ore, hydrocarbons, water, …). However, for the Moon, there remains a significant gap in knowledge of the physical and geophysical properties of the lunar subsurface and how they may be linked to water content. Further, excavation on the moon relies on a strong understanding of the mechanical properties of the lunar regolith. As the strength of the lunar regolith is expected to depend strongly on water ice content [1], it is key to understand the quantity of water ice within the soil to plan excavation and design the tools to be used.

To address this knowledge gap, we conducted a laboratory study on icy lunar soil simulants, to determine the properties of icy regolith under controlled conditions.

Materials and methods: Based on NGI's experience testing permafrost soil in the laboratory [2], we first established procedures for preparing icy lunar soils samples with high repeatability. For this, we prepared a suite of cylindrical samples of icy lunar regolith simulant (Exolith Lab's LMS-1 Lunar mare simulant) samples using dry pluviation (fully saturated) and moist tamping (5- 20 % water saturation). See an example of a prepared sample in Figure 1a. Sample quality was assessed using X-ray Micro-CT imaging to ensure uniform density throughout.

With the sample preparation method established, a suite of new samples was made to cover a larger range of dry density and initial water saturation, and include repeat tests to assess sample variability. For each prepared sample, we performed measurements of the geophysical, geotechnical, with varying amounts of porosity/void ratio and ice content. Acoustic wave velocity (both P- and S-wave) measurements were made in the axial and radial directions. Electrical resistivity (DC) measurements were made along the sample axis. Finally, Unconfined Compressive Strength (UCS; see Figure 1a) tests were conducted within a climate-controlled chamber. To determine the spectral reflectance properties of the icy lunar simulants, samples were also prepared for hyperspectral imaging (in the ~400 – 2500 nm range; see Figure 1b), with the aim of distinguishing mineralogy as well as ice content and crystal size.

Results: The laboratory results show a clear increase in P- and S-wave velocities with increasing ice content, while electrical resistivity decreases with increasing ice content. The strength of the material also increases when the ice content is increased from 5 to 20%.

Preliminary results show a positive relationship between ice content and depth of spectral absorption features around 1450 and 1950 nm. Furthermore, spectral mixture analysis and support vector machine (SVM) algorithms [3] are being applied to the datasets to classify minerology of the pure simulant samples without ice and with various ice concentrations.

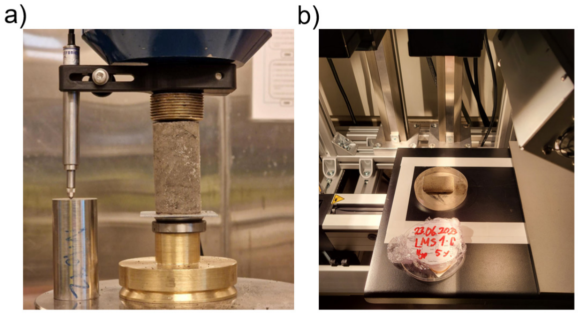


Figure 1. (a) Uniaxial compressive strength (UCS) testing of a cylindrical sample of LMS-1 lunar mare simulant containing frozen water. (b) Hyperspectral imaging of a similar sample (at Norsk Electro Optikk).

Conclusion: Through these experiments we provide a method for preparing samples of icy lunar regolith simulant in a reproducible way. We demonstrate the impact of porosity and water ice content on the geophysical and mechanical properties of the lunar regolith. The sensitivity of geophysical and spectral reflectance properties to ice content holds promise for exploration for water ice and other volatiles within the shallow lunar subsurface. Beyond determining the ice content, the data provided in this study may be used to infer the mechanical properties of the icy regolith, thereby obtaining valuable information for excavation.

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Caves as Planetary Analogs for GPS Denied, Low-Light Mapping and Navigation in Rugged Environments. W. E. King[1], M. R. Zanetti[1], E. G. Hayward[1], and K. A. Miller, [1]NASA Marshall Space Flight Center, 4600 Rideout Road, Huntsville, AL 35812, United States. (Contact: walter.e.king@nasa.gov)

Background: The Kinematic Navigation and Cartography Knapsack (KNaCK) team is developing tools that enable ultra-high resolution terrain mapping and navigation using mobile light detection and ranging (LiDAR) and simultaneous localization and mapping (SLAM) algorithms in fully GPS-denied and unilluminated environments [1, 2]. The backpack mounted LiDAR instrument under development by our team demonstrates the potential of mobile SLAM LiDAR for use in challenging surface environments such as steep walled craters and permanently shadowed regions as well as for lunar, planetary, and terrestrial cave exploration, study, and utilization [3].

Caves as Planetary Analogs: The lunar south pole has rugged and irregular terrain, difficult illumination conditions (extremely low angle of incidence sunlight), and no access to GPS. Lava tubes and subsurface voids on the Moon, Mars, and other planetary bodies will be similarly challenging. Terrestrial caves are excellent analogs for these conditions, providing a proving ground to refine technology for mapping and navigation on other worlds while advancing the State of the Art for terrestrial cave survey. The overburden above cave passages blocks ingress of both light and GPS signals. Highly irregular geometry challenges scan matching algorithms and frequent jostling of the instrument due to rugged and confined terrain interferes with the accuracy of dead reckoning based on inertial measurements. These conditions are similarly challenging to other lunar surface technologies. The responsible use of terrestrial caves as planetary analogs could benefit a wide array of technology development efforts.

Field Work: The KNaCK instrument was used to map two terrestrial caves: Three Caves in Huntsville, AL, and Lava River Cave, a lava tube in northern AZ. Data from Three Caves was collected in 6.5min, capturing a substantial portion of a maze-like complex with only a 370m traverse. Data from Lava River Cave was collected in 44min over 1100m. The maps produced contain 18.4M and 44.8M points, respectively, after post-processing.

Results: The accuracy of the Lava River Cave scan was compared to an existing survey of the cave produced by the Central Arizona Grotto (Fig.1). The LiDAR map is highly accurate at local scale, recording the morphology of the cave in cm-scale detail. However, there is notable drift from the survey at global scale. Continued testing in cave environments offers an opportunity to tune SLAM parameters and experiment with constraining solutions with other data sets (such as survey data or radio location stations).

Acknowledgements: NASA MSFC contributors are supported by NASA STMD ECI program and SMD ISFM programs. The authors thank Ray Keeler, Paul Jorgenson, and the Central Arizona Grotto for graciously providing survey data, radiolocation data, and the original 1984 map, as well as assisting on the day of the scan.

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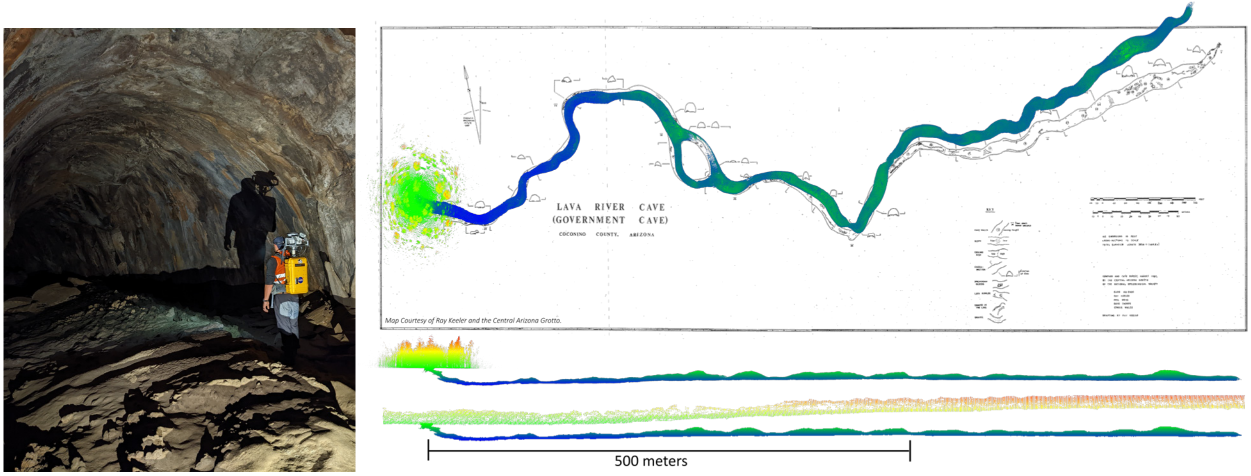

Figure 1. Lava River Cave: (left) scanning borehole passage, (top) LiDAR map overlaid with traditional cave map, (middle) profile view of LiDAR map, (bottom) NAIP Point Cloud DEM overlaid with LiDAR map.

Evaluation of Lunar Dust Mitigation Technologies on the Moon and in Ground Simulators J. Kleiman, Integrity Testing Laboratory (ITL), Inc., Markham, Ontario, Canada, (Contact: jkleiman@itlinc.com), and Z. Iskanderova, AZ SMART Corp., Toronto, Canada

The interaction of materials with regolith dust and other lunar environmental factors, present on the Moon and on the outside of the future Gateway Lunar station may lead to permanent change or complete loss of the thermal, optical, and other functionalities that could potentially lead to catastrophic failures. Among these factors, lunar regolith dust is the most aggressive, causing the main problems. Several general principles are now being identified to prevent sticking of lunar dust simulant and accumulation on surfaces in vacuum conditions. Through a series of experiments in ITL-developed Lunar Simulators, we identified that there is a strong need for a combined - passive and active - dust mitigation approach. This was demonstrated practically in a number of our experiments with advanced external pristine space materials, as well as materials with special surface treatments and with deposited special thin functional coatings.

ITL recently initiated a program to evaluate, further develop, and enhance its unique cornerstone lunar Dust Mitigation Technology (DMT) for sensitive materials on external space structures. In our experiments we achieved Lunar dust simulant mitigation and enhanced surface durability of some important structural materials using this DMT technology [1-3]. In the framework of this program, ITL prepared a set of DMT-treated samples for inclusion in the "Regolith Adherence Characterization (RAC) Payload" funded by NASA and developed and built by Aegis Corporation (formerly Alpha Space Test and Research Alliance) [4].

The RAC Payload mission will determine how lunar regolith dust sticks to a range of advanced external functional space materials and coatings exposed to the lunar environment during the lunar daytime at different phases, i. e. 1) on landing, and 2) during routine lander operations [4]. Advanced space material samples, such as thermal control polymers, thermal control paints, and space textiles, some of them with special coatings and surface treatments, have been provided by NASA, the US academia and industry, including also ITL samples from Canada.

To understand the results of the lunar exposure RAC experiment, we initiated and are conducting in our Lunar Environment Simulator (upgraded for this project) a series of experiments on interaction of lunar dust simulants with samples similar to the RAC Payload experiment as well as with samples of general interest for lunar applications. Based on information in the open literature, we collected or tried to reproduce a significant part of the RAC materials, to expose them to lunar environment conditions, including vacuum, lunar dust simulants, VUV, charging effects, electrons, etc., in the vacuum lunar environment simulator. It is very important, in developing materials with Lunar dust mitigation properties, especially for long-term applications, to consider all environmental factors, like T-extremes, charging-discharging threats, etc., in combination with the Lunar dust environment. These data will be used for future comparison with the RAC results that will include a series of optical images of the samples, obtained in transmitted and/or reflected light and transferred to Earth.

We propose to normalize the data on accumulation and retention of lunar dust simulants to various space material surfaces to a standard (etalon) material with predictable values for these two parameters. As such a material, we propose to use a common space polymer film material – KaptonHN that, as we observed, has very low accumulation and retention values for the used lunar dust simulants, regarding other pristine external sensitive space materials. This approach allows evaluating, comparing and understanding better the obtained results on interaction of lunar dust with different materials.

Keywords: Lunar dust mitigation, RAC Payload Lunar Mission, Lunar Environment Simulation

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Ground-based technology for simulated planetary environmental testing J. Kleiman, S. Horodetsky, V. Issoupov and V. Verba, Integrity Testing Laboratory Inc., 80 Esna Park Drive, Units #7-9, Markham, ON, L3R 2R7 Canada (Contact: jkleiman@itlinc.com)

The Moon is a hostile environment for human survival and equipment. The most troublesome characteristics of the lunar environment are the vacuum (which leads to outgassing), solar and cosmic radiation, micrometeorite impacts, the surface temperature regime, and the ubiquitous dust particles. Facilities for laboratory simulation of lunar conditions had evolved along with increased knowledge of the planetary conditions on the Moon, starting with very simple simulation chambers to highly sophisticated systems. In a multi-year program funded by the Canadian Space Agency [1], ITL Inc. has developed and created a prototype of a Planetary Environmental Simulator/Test Facility that included a modular design stainless-steel vacuum chamber to simulate ultra-high vacuum conditions, lunar dust, UV radiation, thermal conditions/thermal cycling in the appropriate temperature range, as well as simple fixtures and test rigs enabling to conduct mechanical testing and the ability to recreate the darkness conditions present on the back side of the Moon [2-4].

Based on the accumulated experience, we, presently, develop and manufacture specific environmental testing equipment to be used for ground-based simulation of the harsh conditions of the Moon in a more efficient way. This included the creation of more efficient ways of interaction of dust particles with the samples, higher vacuum conditions, better correlated simulation scenarios, more realistic thermal and illumination environments, and addition of charged particles sources to simulate the possible effects of the solar wind, an environmental factor that is also present on the Moon surface and to be able to study the effects of charging on dust mitigation. A methodology was also developed for appropriate dust simulant preparation and conditioning prior to start testing in the simulator test chamber [5].

An overview of ITL efforts will be presented in development of a number of lunar environmental simulator/test systems designed for testing and service life evaluation of candidate spacecraft materials and planetary exploration surface systems, such as space robotic hardware, planetary rover's components, degradation-sensitive mechanical systems with moving parts, spacesuit materials and components, optical equipment, solar panels and radiators, thermal control and other special coatings.

References: **[1]** CSA Contract 9F028-071181/016/MTB (2009-2011A) Planetary Environmental Simulator/Test Facility for Future Space Exploration Missions; **[2]** J. Kleiman, S. Horodetsky, V. Sergeyev, V. Issoupov (2006) Critical Review of the Design of Space Environment Simulators: Lessons Learnt Proc. of the 10th Int. Symp. on Materials in a Space Environment / 8th Int. Conf. on Protection of Materials and Structure from the LEO Space Environment (Collioure France) June 19-23; **[3]** J. Kleiman, S. Horodetsky and V. Issoupov (2011) A Planetary Environmental Simulator/test Facility Proc. of the 10th International Conference on Protection of Materials from Space Environment –ICPMSE-10J, eds. J. Kleiman, M. Tagawa and Y. Kimoto (Springer Publishers) pp 355-370; **[4]** J. Kleiman, S. Horodetsky, V. Issoupov and V. Verba (2014) New Challenges in the Ground-based Technology for Simulated Planetary Environmental Testing Proc. 28th Space Simulation Conference, November 3-6, 2014 (Westin-BWI in Linthicum, Maryland) pp 213-229; **[5]** Lunar dust simulants vacuum testing Protocol in Baseline Lunar Dust Simulant Vacuum Testing for Large Surface UUTS (2014) Integrity Testing Laboratory Report ITL-012914-14027-2M Submitted under Subcontract #26340 Dust Mitigation Technologies (Moon, Mars) Contract SC-26340/922250)

Studies on Plume-Regolith Interactions under Lunar and Martian Conditions.

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Introduction: This is a summary of our recent studies on plume-regolith interactions under lunar and Martian conditions. Understanding the nature of plume-regolith interactions is vital in the design of future space missions. The regolith ejecta produced by these interactions presents numerous risks to the integrity of the spacecraft and the success of the mission.

Comprehensive experimental investigations of the flow patterns resulting from under-expanded axisymmetric jets that impinge on surfaces and structures with and without regolith simulants in a near-vacuum environment that emulates the atmospheric conditions of celestial bodies such as the Earth's moon and Mars's moon have been conducted. The experiments were performed within a specialised plume regolith facility at the University of Glasgow. The facility, which has a 12 m3 test chamber can achieve an ultimate pressure of around 1 Pa and maintain the required nozzle stagnation-to-background pressure ratio for 2.5 seconds in steady and pulsing operational mode. Scaled versions of convergent-divergent nozzles are installed at stand-off heights from a surface equipped with pressure transducers. The nozzle stagnation chamber can be heated to a temperature of 1000 K to attain Reynolds number similitude. We have experimented with two modes of nozzle operation, namely steady and pulsed modes. A FLIR infrared camera was used to record the plume impingement's thermal profile on the surfaces and structures. The particle image velocimetry (PIV) approach has been used to track the liberated particles. The difference in the ejected vector field among the chosen simulants shows how regolith physical properties affect lunar and Martian plume surface interactions.

In the numerical part of our work, a fully transient code for solving rarefied multiphase flows, rarefiedMultiphaseFoam, has been developed with models to account for solid-solid interactions and applied to rocket exhaust plume-lunar regolith interactions. Two different models to account for the solid-solid collisions are considered; at relatively low volume fractions, a stochastic collision model, and at higher volume fractions the higher fidelity multiphase particle-in-cell (MPPIC) method. Both models predict cratering at early times and similar dispersion characteristics as the viscous erosion becomes dominant.

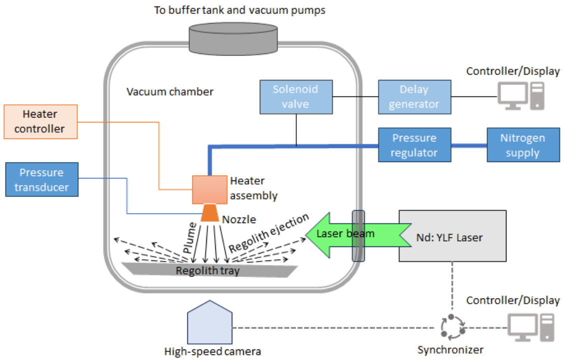

Fig 1: Experimental setup.

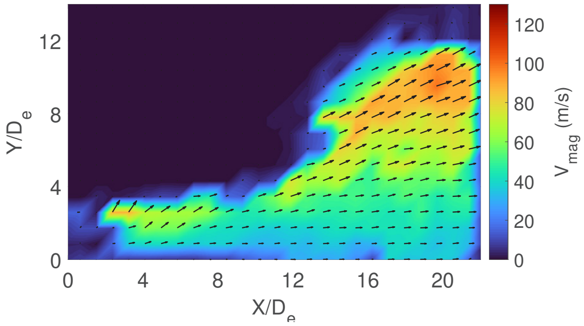

Fig 2: Vectors of ejected particles from the plume interaction.

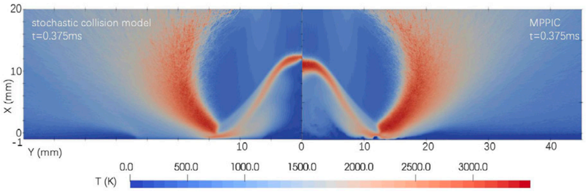

Fig 3: Comparison of gas overall temperature field between the stochastic collision and MPPIC.[1]

Acknowledgements: The authors wish to express their gratitude to our multiple external collaborators and our funder ESA-ESTEC.

References:

[1] Cao Z., White C., Agir M.B. and Kontis K. (2023) *Frontiers in Mechanical Engineering*.

Slanted Grousers for Planetary Rover Wheels.

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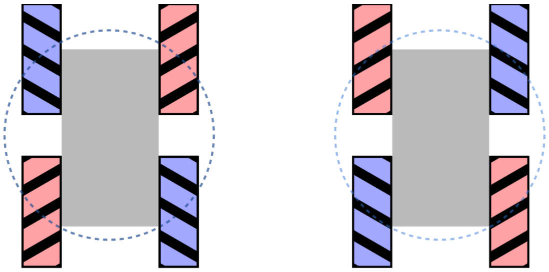
Introduction: Planetary surfaces are irregular and dusty, so rovers will require robust ground-contact hardware, both for exploration and future construction. Fixed-axle wheels remove the complexity of steering, but differential turning can dig into the terrain rather than move the rover. We show slanted grousers can make fixed-axle rover turns require less wheel torque and energy.

Background: Wheel grousers (lugs) of different types have been well studied for agriculture, varying the grouser count, size, spacing, and angles [1]. More recent systematic testing of various grouser heights [2] and shapes [3] in dry sandy terrain is more applicable to rover design. Slanted or fully helical grousers [4,5] have been evaluated experimentally and via simulation.

Slanted grousers produce less torque variation during open cage wheel rotation [1]. They do induce side forces that are dynamic and large, but still smaller than pull forces [3]. Figures 1 and 2 explore possible rover configurations using various combinations of slanted grousers.



(a) Radial slant (b) Tangent slant

Figure 1: View from underneath a 4-wheel rover, showing (a) grousers slanted along the **radius** of the turning circle, which makes zero point turns easier for the robot to initiate; and (b) grousers slanted **tangent** to the turning circle. Right/left handed wheels are shown in blue/red for clarity.

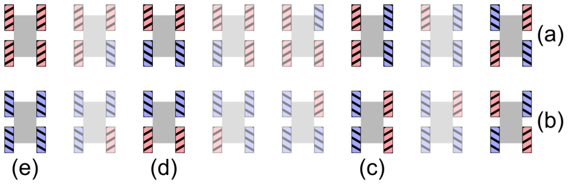


Figure 2: All 16 possible wheel configurations: (a) radial and (b) tangent as above, (c) front-back [3] and (d) left-right symmetry, and (e) uniform slant. Odd "1 out of 4" configurations shown in gray.

Testing: Our six wheeled testing rover masses 75 kg and has a 1.2 meter roughly square wheelbase, with 285 x 180mm wheels with 24 helical grousers 7mm high (5% of radius [2]). The front wheel axles mount directly on the frame, while the middle and back wheels pivot on a bogie bar. The wheels do not steer, so the robot turns using only tank-style differential drive.

On loose gravel, we performed 360 degree zero point turns under torque control with the rover's front and back grousers slanted differently.

Grouser Slant	*Energy/turn 70% torque*	*Energy/turn 60% torque*	*Min turn torque*
(a) Radial	7.1 kJ	8.2 kJ	40%
(c) Front-back	7.8 kJ	8.9 kJ	50%
(b) Tangent	10.3 kJ	11.5 kJ	55%

Figure 3: 6-wheel rover in radial slant grouser configuration, after four full rotations on gravel.

Conclusions: Radial slanted wheel grousers allow heavier rovers to make zero-point turns without steering hardware. Work continues to quantify this effect and validate its load and terrain limits. Tangent slant may produce less sinkage and terrain disturbance in some situations, which we would like to quantify.

One challenge is slanted grousers may require separate left and right handed spare parts, while straight grousers use only one wheel type.

For configurations (a-c), turning each helical wheel in opposing directions may allow holonomic omnidirectional translation with a sufficiently smooth wheel, and we are exploring how the grouser and terrain types influence this possibility.

References: [1] Watyotha C. et al. (2001) *J Terram.* 38, 1-14. [2] Inotsume H. et al. (2019) *J Terram.* 85, 39-57. [3] Nagaoka K. et al. (2020) *J Terram.* 90, 23–30. [4] Thoesen A. (2019) ASU PhD. [5] McBryan T. (2022) ASU MS.

Resource Extraction from Solution using Self Organizing Wetland Bioreactors (sowbs).

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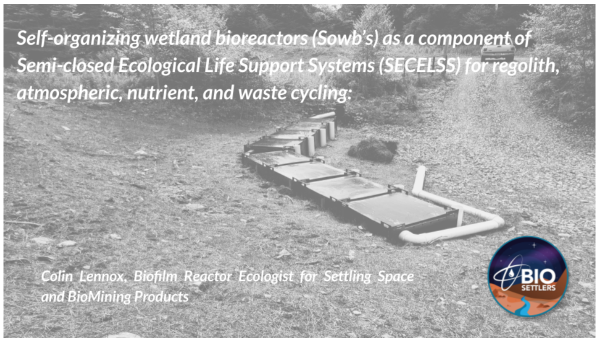
Introduction: The biotic and abiotic interactions of microbial biofilms living in natural wetlands cycle organic and inorganic matter. This complex organization, and the flux of matter in and out of natural wetlands, can be replicated and made to do work for the purpose of biological in-situ resource utilization (bisru). By integrating oxidizing and reducing sowbs into an enclosed environmental life support system (eclss), all primary waste streams due to human habitation and needs can be cycled and comingled for increased efficiency and breadth of products for an average savings of ~90% of the abiotic activation energies. The biology catalyzes the cycling interactions "for peanuts" and can contain, harness, and sustain, hypothetically, all of the metabolic pathways found on Terra. The sowbs become the point of interaction between incoming regolith, sewerage, agricultural waste, and atmospheric gasses. Terran commercial examples of uses/products are manganese oxides up to 85% purity, rare earth elements, dense iron oxides, sulfuric acid, degradation of some pharmaceuticals and Fecal coliforms, and methane production and "purification".

Main Slide and Featured Sowbs:



Self-organizing wetland bioreactors (Sowb's) as a component of Semi-closed Ecological Life Support Systems (SECELSS) for regolith, atmospheric, nutrient, and waste cycling:

Colin Lennox, Biofilm Reactor Ecologist for Settling Space and BioMining Products

Lunar Advanced Surface Electrification (LASE) P. Lubin[1], P. Meinhold[1], P. Srinivasan[1], N. Rupert[1], A. N. Cohen[1], J. Webb[1], [1] University of California - Santa Barbara, Broida Hall, Santa Barbara, California, 93106, United States (Contact: lubin@ucsb.edu)

Introduction: The industrial and technological revolution only proceeded once large amounts of power became available, first in mechnical form in the 19th century, and then in electrical form in the 20th century. The latter is critical to advancement in space, and particularly on the lunar surface. By beaming energy from a directed energy (DE) laser either in single element (DESE) or Phased Array (DEPA) in both "point to point" and "store and forward" topologies, we enable a wide variety of lunar operations such as those in permanently shadowed regions (PSR) and long range tower-to-tower, surface-to-spacecraft, spacecraft-to-surface and spacecraft-to-spacecraft power beaming. This system is inherently modular, scalable, and multi-functional, and represents a path forward to electrification of the lunar surface that can handle a large and diverse mission space.

Wireless power transmission: We envision the application of DEPA / DESE technology to long-range lunar point-to-point power beaming using towers. As an example, the use of towers 100m tall would enable point-to-point beaming across >35km baselines. The DEPA system is run in a single spatial mode while DESE can be single or multi-mode. While a multimode system is much simpler to build and deploy and is the basis for our LuSTR program, it is not suitable for very long range applications, such as those where a spacecraft is the target or where a spacecraft is the intermediary between distant ground locations. An extreme example of this is our Earth-to-lunar-surface mode.

Laser photovoltaics: The use of beamed power transmission requires the use of laser photovoltaics (LPV) in order to convert the laser light into electricity at the target. We have demonstrated >28% conversion efficiency in Si and are working with on InGaAs converters as part of our LuSTR program, which has achieved >45% conversion efficiency at 1 micron. Additionally, the optical power that is not converted to electricity can be converted to heat and stored in a thermal battery, which is especially useful during the lunar night and could enable near-unity conversion.

High-flux application: In cold environments such as lunar night applications, the LPV can be run at high flux which can raise the efficiency. Running the LPV at higher flux lowers the mass per unit electrical powered delivered which can be critical for deep space ion engine missions. With current designs we are at 1 kg/kW$_e$ and with new designes we should be able to achieve ~ 0.1-0.2 kg/kW$_e$.

Wired power transmission: As part of our Watts on the Moon Program (WOTM), we present an additional solution to the problem of transmitting power across large distances on the lunar surface, namely that of direct wired transmission. We have developed a very effective and low mass system which allows for high power applications over a broad temperature range anywhere on the lunar surface. Our hybrid cable solution enables operation in both daytime and nighttime conditions, from 30K – 400K, and included energy storage capable of surviving the lunar night, as discussed below.

Combined wireless and wired transmission*:* Our two solutions allow for varying system topologies such as the beamed power option for applications that require it (i.e. mobile applications), as well as a multi-point hybrid solution where both mobile targeting using beamed power and fixed power transfer using cables are utilized. This enables extreme flexibility and scalability, and offers a wide variety of options for the future. We have shown in prior work that this wired solution allows transmission line efficiencies over the transmission line of ~85-90% for the "warm case" and near 100% for "cold case" with a hybrid cable mass of ~14 kg/km.

Surviving the lunar night*:* In designing sustained operations on the lunar surface, the problem of surviving the 14-day lunar night is a critical issue to solve. We have shown in our WOTM work that relatively modest cryogenic engineering can be applied to the case of electrical and thermal batteries, which can be designed to survive at room temperature for the entire lunar night. The battery packs need a thermal control system in order to maintain proper temperature since at some points in the charge/discharge cycle the batteries will generate more heat than at other times. By thermally isolating the packs from the environment, this waste heat can be used to keep the batteries and control systems near optimal operating temperature, and we are designing the system such that it allows the battery pack to radiate excess heat into cold space periodically as needed.

References:

[1] P. Lubin (2022) *World Scientific.*

World-Wide Commercial Lunar and CISLUNAR Ground Network for LunA-10. B. Malphrus[1] M. Cosby[2], M. Gnat[3], Pierre Lagadrilliere, R. McNeil[4], and T. Strydom[5], [1]Morehead Space Technologies, Morehead, KY, 40351, [2]Goonhilly Earth station Ltd, UK, [3] Deutsches Zentrum für Luft und Ramfahrt, e.V., Germany, [5]South African National Space Agency, [6]SpaceOps NZ. (Contact: b.malphrus13@gmail.com)

Introduction: Large aperture ground stations are required to support the upcoming cislunar and lunar economies for both high data-rate communications with surface assets and orbiting relays, and for providing high-precision radiometric data working with orbiting spacecraft for positioning, navigation and timing (PNT). Large aperture ground stations are scarce and are extraordinarily expensive to build, maintain, and operate. A new 32-meter station with NASA Deep Space Network (DSN) capabilities can exceed $40M. A minimum of six antennas spaced approximately 120° apart around the globe are necessary for continuous coverage and effective PNT that requires radiometric data from the North and South hemispheres. A strategy to utilize and upgrade existing large aperture stations as the basis for an affordable commercial lunar ground network is propsed.

A study to examine the validity of the concept is based on assessing the state of six independently owned, large aperture stations (>20 m) around the world that have formed a "loose" partnership of lunar-capable ground stations, the Consortium of Large Aperture Ground Stations (CLAGS). CLAGS was established in 2023 to provide integrated services for the lunar economy.[1] The CLAGS study will investigate potential network architectures, cyber-security solutions, implementation of common state-of-the-art systems to comply with lunar infrastructure standards and a common scheduling system and user interface, leading to a System Concept Review (SCR) level design.

Summary- State-of-the-Art: While Optical Laser communications (lasercom) is a key component of the LunA-10 architecture, high data-rate RF communications are required for redundancy and to augment proposed lasercom systems, especially for PNT through precise radiometric measurements using lunar orbiting spacecraft. Innovative spacecraft communications systems at higher frequencies (X, Ka-bands) combined with modern modulation and coding schemes, with extremely low noise receiver systems and large aperture reflectors, can achieve 10s to potentially 100s of Mbps data throughput directly to Earth from lunar assets.

There are numerous potentially effective solutions toward providing high data-rate communications and precise radiometric data for PNT. These include synthesized arrays, implementation of new large-aperture ground stations, and using existing large aperture antennas. Notwithstanding great progress, the difficulty of establishing complex autocorrelation systems and kilowatt power uplinks with synthesized arrays present significant technological challenges. Implementing a new, world-wide network of 20–34 meter deep space capable ground stations could cost over $400M. Upgrading existing, often underutilized radio telescopes presents a cost-effective strategy able to bring a first-generation commercial lunar network on-line effectivel and quickly.

Proposed Design: CLAGS was established with the intent of providing TT&C and PNT services to lunar missions [1]. The existing (4) stations along with (2) in development are shown below. Each of the stations is extremely capable and several have already supported lunar missions.

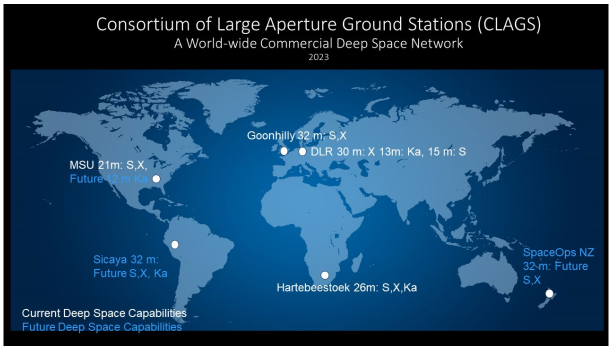


Figure 1 Consortium of Large Aperture Ground Stations- Current and Future Ground Stations

Ultimately, all the CLAGS stations will be upgraded to incorporate common technologies, a common user interface, a common scheduling system, and a unified, secure network circuit to support LunA-10 operations.

References:

[1] B. Malphrus, M. Cosby, M. Gnat, R. Falcone, R. McNeil, T. Strydom, (2023) *Consortium of Large Aperture Ground Stations (CLAGS) Initiation Concept, 3.16.2023*

The Flexible Logistics & Exploration (FLEX) Rover Lunar South Pole Mission in mid-2026.

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

Introduction: NASA and private industry investments will soon make it possible to land unprecedented amounts of cargo on the Moon at a regular cadence. Venturi Astrolab, Inc. (Astrolab) is developing the multi-functional Flexible Logistics & Exploration (FLEX) rover with this burgeoning environment in mind. FLEX is a Lunar Terrain Vehicle (LTV)-class, semi-autonomous, remotely-operable, rover that can carry two suited astronauts and all their associated equipment, tools, instruments, and samples. (Figure 1). In March 2023, Astrolab announced that it had signed a launch service agreement with SpaceX to send an uncrewed version of FLEX to the lunar south polar region as soon as mid-2026 on a Starship Launch & Landing System. Astrolab has already signed several customer reservation agreements for this mission, totaling hundreds of kilograms of customer payloads and hundreds of kilograms of capacity remains available for additional customers.

Figure 2: FLEX's modular payload interface and novel mobility system enable it to perform a multitude of functions, including crew transport, outpost logistics, robotic science, and infrastructure deployment

FLEX can accommodate payloads with volumes totaling in excess of 3m^3 and masses of up to 1,500 kg. The FLEX rover's unique commercial potential comes from its novel mobility system architecture, which gives it the ability to pick up and deposit modular payloads in support of human operations, robotic science, exploration, logistics, infrastructure deployment, site survey/preparation, construction, maintenance, & repair, resource utilization, and other activities critical to a sustained presence on the Moon and beyond.

Robotic Arm & Payload Mezzanine: FLEX is equipped with a 2.4m long, six degree-of-freedom robotic arm with a dust-tolerant quick disconnect end effector that is used to attach-to and extract payloads, instruments, and tools that are housed in a mezzanine below the arm (Figure 2). Each of the 15 payloads in the mezzanine can be as large as a 12U cubesat (22cm x 22cm x 36cm) and 25kgs. In addition to deployable customer payloads, the mezzanine can contain instruments or other implements such as a scoop for collecting samples or transferring regolith.

Figure 1: Astrolab's 6-DoF Robotic Arm and Payload Mezzanine attached to the FLEX rover.

Analog Testing: Astrolab has developed a full-scale, fully-functional terrestrial proof-of-concept FLEX rover and has conducted multiple field tests at analog sites in the California desert. At these field trials, FLEX was used to conduct demonstrations of various activities and operational scenarios that will be required on the Lunar surface [1]. Recent testing included an end-to-end in-situ resource utilization (ISRU) demonstration (Figure 3). This test included the transport and deployment of a 5kW vertical solar array tower (VSAT) mockup and an ISRU pilot plant (1.5m x 1m x 1m) mockup. The ISRU plant included a cable spool that connected the VSAT to the plant. After deploying this equipment, the FLEX robotic arm extracted a scoop implement from the payload mezzanine and used the scoop to collect and deposit feedstock material into the ISRU plant. This test successfully demonstrated how an ISRU pilot plant of a meaningful scale could be deployed and operated on the lunar surface in a series of practical steps using FLEX.

Figure 3: Astrolab recently conducted an end-to-end ISRU plant deployment demonstration at an analog test

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

Exploring the Impact of Harsh Lunar Conditions on Physical and Mechanical Properties of Lunar Building Materials

Authors: A. N. Narvasa[1], M. Miletić[1*], E. Torresani[1], D. Cortes[2]

Abstract:

The NASA Artemis exploration initiative is geared towards establishing a sustained lunar presence, necessitating repeated visits to the same site and the creation of robust and enduring launching and landing pads (LLPs). Several methodologies for utilizing in-situ lunar regolith in construction, including sintering, grading, compacting, and polymer spraying, have been proposed and studied. Despite the promising outcomes seen with some of these techniques, a significant gap in knowledge persists regarding their performance under extreme temperature fluctuations on the lunar surface. Presently, no research has delved into how these construction methods and materials endure the severe lunar temperature conditions. As a result, this study's overarching objective is to comprehensively comprehend how different LLP construction approaches respond to the challenging lunar environment. This is achieved by conducting experimental investigations that analyze the effects of extreme temperature variations on the physical and mechanical attributes of three distinct building materials used in LLP construction.

To achieve this goal, the study employed the LHS-1 lunar simulant as the base material, accurately mimicking the composition of regolith found in the moon's highland region. The investigation focused on three distinct construction methods: enhancing the regolith with Xantham Gum biopolymer (XG), implementing cold isostatic pressing (CIP), and utilizing spark plasma sintering (SPS). The study analyzed the impact of extreme lunar temperatures spanning from -180 °C to 125 °C. To investigate the influence of thermal cycling on the macroscopic mechanical behavior of the specimens, unconfined compression tests were conducted. Additionally, scanning electron microscope analysis in conjunction with image analysis was performed to examine the microstructure of the specimens, while the evolution of bulk density with thermal cycling was assessed using the Archimedes method.

The comprehensive outcomes of the experiments unveiled that among the trio of methods, the SPS samples displayed the highest bulk density and the least microporosity. Following in sequence were the CIP method and, ultimately, the XG method. Consequently, the specimens derived from the SPS technique demonstrated markedly enhanced macroscopic mechanical characteristics, surpassing those achieved by the other approaches by a substantial margin. Nonetheless, despite their exceptional macroscopic mechanical performance prior to thermal cycling, the SPS specimens showed the swiftest decline in their physical and mechanical attributes when subjected to thermal loading. This decline can primarily be ascribed to their densely compacted microstructure and elevated bulk density, rendering them more vulnerable to the detrimental effects of thermal cycling.

Keywords: Regolith, Launching and Landing Pad (LLP), Xanthan Gum, Cold Isostatic Pressing (CIP), Spark Plasma Sintering (SPS), Cyclic Thermal Loading

A Coordinated International Lunar Resource Prospecting Campaign: Beginning the Coordination.

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Introduction: This initiative began in 2021 [1,2] and has grown since then with presentations at IAC and the Luxembourg Space Resources Week. (e.g., [3]) and a revised paper is currently under consideration for publication in Acta Astronautica. In 2022, two Lunar Surface Science Workshops were held on this subject [4,5] and further developed the concept. Among the findings were the definition of data types from such a campaign and the coordinating body should be a "non-governmental agency (NGO)".

Current & Scheduled Missions: The following missions currently operating at the Moon and can focus on polar volatile resources: NASA's Lunar Reconnaissance Orbiter (LRO); the Korean Pathfinder Lunar Orbiter (KPLO); the orbital component of the Chandrayaan-2 mission and the Chandrayaan 3 lander from India. Other missions are scheduled to go to the Moon in the next 5 years: Lunar Trailblazer (NASA orbiter); the Volatiles Investigating Polar Exploration Rover (VIPER); the LUnar Polar EXploration mission (LUPEX) from Japan and India (lander and rover); NASA's Polar Resources Ice Mining Experiment-1 (PRIME-1) ISRU demonstration; ESA's Package for Resource Observation and in-Situ Prospecting for Exploration, Commercial exploitation and Transportation (PROSPECT) ISRU demonstration; the Canadian Lunar Rover Mission (LRM). The coordination of lunar resource prospecting represents opportunities for international diplomacy in an era that desperately needs it.

Beginning the Coordination: The coordinating "NGO" could be the lunar community, at least initially. As such, we have started a grassroots approach focusing on missions highlighted above. The orbital missions can return multiple, diverse datasets for the same locations so surface assets could be accurately deployed to obtain the granularity of data needed to define the reserve potential there. We believe this is the vital next step in underpinning sustainability of human exploration of the Moon and also helping to establish a vibrant cislunar economy. But which sites should be targeted? The largest craters at the south pole may not be the best targets for initial surface exploration due to accessibility. ShadowCam on KPLO has the potential to map routes into and out of PSRs [6]. Therefore, part of this effort will be to integrate existing datasets for the targets chosen while obtaining new data from the orbital missions, and ground truth data from the landed missions. A start can be made by integrating current datasets for the unnamed medium to small PSRs at the south pole (e.g., [7,8]) around the Artemis landing sites. Site selection can be community driven through hybrid international workshops, & special sessions in established conferences. Products will inform future landed missions to give spatial resolution needed to quantify the reserve potential of each site.

Legal Implications: If this campaign is international in nature, it provides a great opportunity to test and refine the applicable legal framework while being intentional in setting precedents that positively shape the conduct of lunar (and space) resource activities in accordance with the OST. We propose as a beginning 3 foundational features:

- The global relevance of lunar resources requires the involvement of all interested actors, irrespective of their economic & scientific development.
- The variety of data that will be obtained throughout the campaign allows for the possibility to provide benefits to both its participants and the broader science community.

The unprecedented level of cooperation and coordination required for the campaign can be used as a catalyst to accelerate current rulemaking efforts for lunar governance.

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Use of Multi-Functional Lightweight Flexible Fabrics for Chemical and Thermal Barrier Applications

S.J. Nicholson[1] and P.C. Mann[2], [1]Kappler, Inc, 140 Grimes Drive, Guntersville, AL 35976, Kappler, Inc, 140 Grimes Drive, Guntersville, AL 35976 (Contact: jnicholson@kappler.com)

Introduction:

Kappler, Inc., a woman and employee owned small business, proposes to address the need for an environmentally inert flexible fabrics that provide a combination of chemical and thermal barrier performance characteristics. Kappler, Inc. has designed, developed and manufactured chemical and thermal resistant fabrics and protective garments since 1976. With more than 26 patents issued or pending, Kappler innovation extends to related accessory and specialty products such as AntiFog Visor technology, the 2N1® Glove System and ChemTape®.

The Zytron® family of fabrics provide a high level of chemical permeation barrier ideal for use in containing and processing hazardous chemicals used during lunar exploration. These fabrics exhibit high levels of puncture and tensile strength. When they are constructed and sealed into containers they can provide pressure resistance.

The Frontline® and Durachem® families of fabrics provide similar levels of chemical barrier performance as well as flame and thermal barrier performance as well. Durachem fabrics provide high levels of abrasion resistance and strength. These fabrics could be considered for barrier liners in permanently constructed habitats to assist in providing and maintaining pressure in those structures. These fabrics can also provide thermal and radiation attenuation characteristics.

In addition to the fabric technologies, Kappler has years of experience in the joinage of fabrics and components of various polymer types and configurations.

These technologies will be presented to address the potential needs of the Lunar Surface Innovation Consortium (LSIC), specifically testing maintenance routines at lunar proving grounds, gradually increasing robotic autonomy while interacting with humans, defining the parameters and constraints of the architecture required to support a sustained presence on the lunar surface, as well as economic and policy considerations.

Past Experience:

Kappler participated with NASA-JSC in a project to provide chemically protective overhoods for ammonia protection for astronauts on the International Space Station (ISS). Kappler Zytron 300 fabric was used to construct the hoods which integrated with existing breathing system equipment.

Kappler worked with Lockhead Martin and utilized Zytron 500 fabric for the vapor containment and detection of hypergolic fuels during transport of THAAD missile launch system on military aircraft.

Kappler provided prototype services to NASA-MSFC for the construction of a lunar rover protective structure for ballistic and radiation protection during long term storage.

Kappler provided design and prototype services to NASA-MSFC for a multi-purpose lunar habitat that would allow for pressurization to assist in the additive manufacturing of permanent structures and landing pads for the lunar surface.

References: No references made.

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

Niecke A.[1], Lüking A.[2], Wiesen L.[3], Rodeck L.[3], Sunny Singh[3], Niehuss G[3]., Schott-Vaupel J.[3], Gries T.[1]
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[3]IMFEX student team
Contact: alexander.lueking@fibrecoat.de

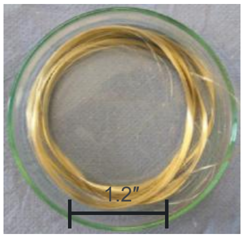
Introduction:

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

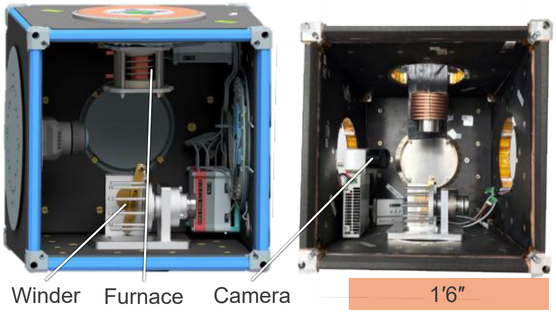
Fibers and textiles made from lunar regolith can unlock this potential and also significantly expand the possibilities for necessary products for lunar exploration. Glass and basalt fibers are commercially available on Earth. With up to 4,000 MPa, they are 100 times stronger in tensile strength than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

Manufacturing MoonFibre on the surface:

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



At the same time, an automatic production concept for the moon was developed. With an induction furnace, 16 kg/24 hours can be produced with only regolith and electrical energy. Spinning trials were conducted in low-orbit at 0g to validate the robustness of the machine with respect to the rocket launch forces and the possibility to produce Lunar regolith simulant fibers at different gravities.



Acknowledgment: MoonFibre is funded by German Aerospace Center DLR.

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

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Leveraging Commercial Flight Testing to Advance Lunar Surface Technologies.

S. F. Ord[1], E. W. DiVito[2], C. E. Tuck[2], G. H. Peters[2], D. D. McCulloch[2], [1]Ames Research Center, Moffett Field, CA 94035, [2]Armstrong Flight Research Center, Edwards, CA 93523.
(Contact: chloe.e.tuck@nasa.gov)

Introduction: NASA's Flight Opportunities program leverages commercial flight providers to accelerate the maturation of space technologies using suborbital rocket-powered vehicles, aircraft flying parabolic trajectories, and high-altitude balloons, as well as orbital platforms that can host payloads in cooperation with NASA's Small Spacecraft Technology program. Exposure to relevant space environments can validate a technology's functionality in a cost-efficient and timely manner, reducing risk ahead of longer, more expensive missions, including missions to the Moon and Mars.

Since 2011, Flight Opportunities has supported over 271 flights with more than 899 tests of payloads. These flight tests have supported the maturation of technologies and research with applications for lunar exploration and the development of resilient lunar infrastructure.

Flight Opportunities presenters will cover the following key points as a resource for researchers interested in maturing their space technologies and engaging with NASA:

- Ways for U.S. researchers from industry, academia, and non-profit research institutes – as well as those from NASA and other government agencies – to engage with the Flight Opportunities program
- How PIs (principal investigators) can make the most of their flight tests and design them with a future lunar application in mind
- Why commercial flight testing has become a best practice for NASA-supported technologies across disciplines
- Resources available for investigators, including a monthly Community of Practice webinar series, the Flight Opportunities newsletter, and one-on-ones with Flight Opportunities team members

Technologies and Research Appropriate for Testing through Flight Opportunities: Under the umbrella of NASA's STMD (Space Technology Mission Directorate), Flight Opportunities advances STMD's mission to rapidly develop, demonstrate, and transfer revolutionary, high payoff space technologies. STMD organizes the agency's technology investments into a strategic framework with focus areas to drive technology development.

Technologies and experiments that fit the four "thrusts" of NASA's Strategic Technology Framework and will enable NASA's future exploration missions are well-suited for flight testing through Flight Opportunities. Examples include:

- GO: Cryogenic fluid management
- LAND: Entry, descent, landing; precision landing, thermal protection systems
- LIVE: In situ resource utilization; advanced thermal management; advanced materials, structures, and construction; advanced habitation systems
- EXPLORE: Advanced manufacturing; small spacecraft systems

Relevant Test Environments: Flight Opportunities facilitates access to a variety of test environments that replicate conditions encountered on lunar missions. Relevant test conditions include:

- Microgravity and weightlessness
- Challenging landing, hazard detection and navigation
- High-altitude solar exposure
- Extreme temperatures and vacuum
- Observation for suborbital and orbital instruments
- Intense spacecraft vibrations
- Atmospheric re-entry
- Radiation

Recent Lunar Technology Testing: Presenters will provide examples of recent testing, including the agency's second TechLeap Prize, Nighttime Precision Landing Challenge No. 1, which aims to advance technology to aid lunar landings in the dark and hazardous region of the Moon's south pole.

In addition, NASA expanded options for evaluating the performance of technologies in lunar gravity via support for new testing capabilities on Blue Origin's New Shepard reusable suborbital rocket system – enabling researchers to test and de-risk innovations critical to achieving the nation's lunar exploration goals, like those of the Artemis program.

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

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

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

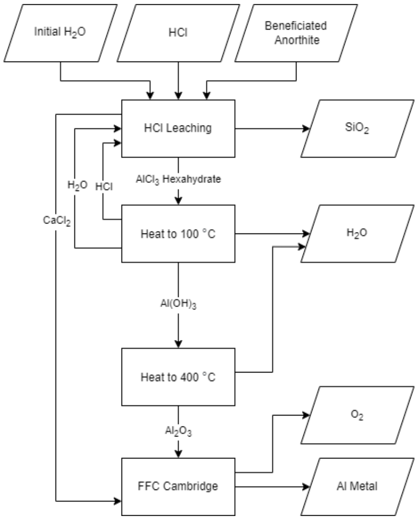


Figure 1: LISAP-MSE flowchart

Methodology:

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

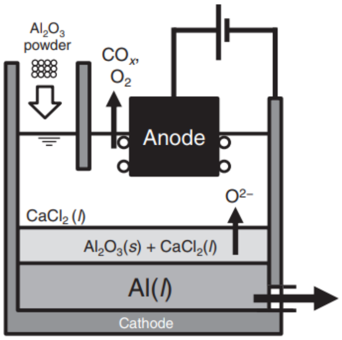


Figure 2: Aluminum Oxide Electrolysis [1]

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

Results:

Leaching of the anorthite using hydrochloric acid has been successfully tested and characterized. Results of the leaching process can be seen in Table 1.

Table 1: Leaching Results

Trial Run	Oven Temp (C)	Time (hrs)	Initial Anorthite Mass (g)	Remaining Silica Mass (g)
1	160	2.5	8	6.3
2	175	2.5	8	5.25
3	175	5	8	4.27
4	180	6.5	8	5.55
5	210	24	8	4.44
6	190	24	8	4.43
7	160	24	8	4.49
8	150	24	8	4.45
9	140	24	8	4.44
10	120	24	8	5.06

The table above shows that after 24 hours, the minimum remaining silica mass was near 4.44g. Looking at the results for each run, it can be concluded that the minimum tested temperature required to drive the reaction to completion was 140 C.

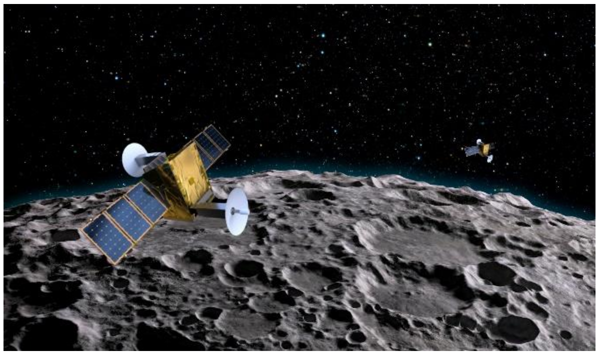
Once the leaching was completed, products were then further processed into alumina. This was done by heating the sample to 1200C. The samples were then characterized using XPS and FTIR which show the correct atomic ratio for alumina and the confirmation bands respectively.

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

Parsec® SmallSat-Based Commercial Lunar Communications and Navigation Service. Lindasy Papsidero[1], [1]Crescent Space Services LLC, 12257 S Wadsworth Blvd, Littleton, CO 80127. Contact: lindsay.papsidero@crescentspace.com

Introduction: Crescent Space Services LLC is a wholly owned commercial services subsidiary of Lockheed Martin (LM), established in 2022 to provide infrastructure-as-a-service for commercial and government lunar missions. As a separate company, Crescent is able to combine LM's deep heritage and reliability in space with the agility of a separate commercial platform and business model. This approach enables Crescent to deliver reliable commercial lunar services at competitive prices, with the speed and flexibility necessary to meet this new emerging market. Crescent operates independently with its own board of directors, leadership team, employees, and tailored commercial processes, while also maintaining the ability to reach back into LM when needed for specialized talent and expertise to deliver these services.

Crescent will own and operate the Parsec® network, a SmallSat-based lunar communications and navigation service beginning in 2026. Parsec offers end-to-end communication and navigation services to lunar surface and orbiting users from two dedicated interoperable relay satellites, providing 24/7 coverage to the South Pole and southern latitudes. Parsec is built on a modular SmallSat spacecraft product line known as Curio™, developed for a myriad of lunar and deep space missions. The satellite is equipped with both high-and low-rate communications relay payloads with software-defined radios. A highly capable payload processor with a flexible software framework enables on-orbit configurability, and will allow the network to scale with additional nodes as the lunar ecosystem evolves. The system is designed to service initial and future mission needs in a commercialized manner, enabling a new class of missions to the Moon.



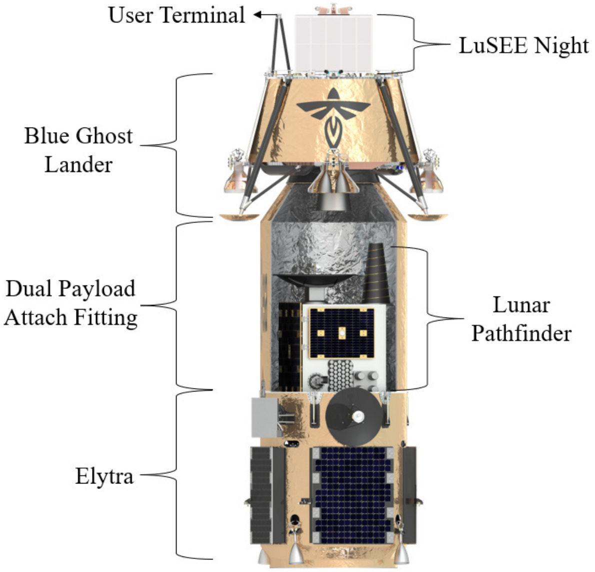
This presentation will start by walking through the Parsec users guide, which will allow the audience to gain an understanding of how to connect to and use the Parsec service. From there, we will invite the audience to a dialogue exploring mission use cases and performance needs in regards to communication, navigation, and timing. We will use this dialogue to ensure these needs are met by the planned services, and to identify additional lunar infrastructure that may be desired or required in this new marketplace.

COMMERCIAL LUNAR SAMPLE RETURN: USING CONTRACTED PLATFORMS FOR SAMPLE DIVERSITY.

S.A. Peterson, W. J. Coogan, and K. O. Scholtes, Firefly Aerospace, Inc. (5900 Highway 183A Leander, TX 78641; sam.peterson@fireflyspace.com).

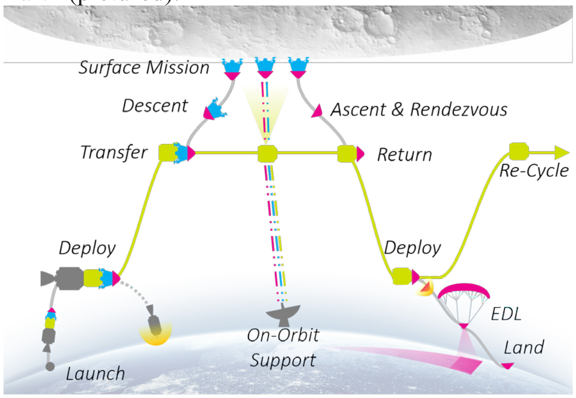
Introduction: Lunar sample return has only been achieved by three entities–each of those a national space program–from a handful of mid-latitude sites. The limited supply of lunar samples on Earth calls for an increased cadence of sample delivery from a greater diversity of sites to better foster scientific research and assessment of resources for future economic and exploration use. Spacecraft presently in preparation for missions supporting NASA's Commercial Lunar Payload Services Program (CLPS), specifically Firefly's Blue Ghost and Elytra platforms, provide the critical building blocks needed to obtain samples commercially at a higher cadence from diverse regions and at a lower cost.

Elements: Firefly's Blue Ghost lander (CLPS 19D and CS-3) and Elytra orbiter (CLPS CS-3 pictured) platforms have nearly identical buses, with the key differences being structural. The Blue Ghost platform is mass-optimized to go to the lunar surface, while the Elytra structure is taken from Firefly's Alpha launch vehicle in order to support substantive payloads. Both platforms are scheduled to have flight heritage in the next three years.



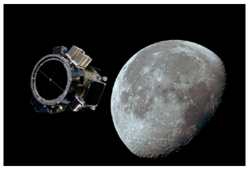
Architecture: Because the Elytra platform uses the same structure and separation mechanism as a launch vehicle designed to carry much greater loads, it is an inherently stackable building block. Four vehicles can fit in a nominal Falcon 9 fairing. The resulting stack can therefore leverage staging to achieve sample return through multiple architectures. As a first example, the stages can expend themselves completely on the way to the lunar surface, delivering a nearly full Blue Ghost lander to the lunar surface. With a sufficient thrust-to-weight ratio, this vehicle has the delta-V required to achieve an Earth re-entry trajectory.

The preferred, though logistically more challenging method, is to follow in the footsteps of Apollo and Chang'e 5 missions. In this example, one Elytra stage remains in orbit while the topmost Elytra of the stack performs a portion of the breaking burn for the lander before being discarded to the lunar surface. The lander reaches the surface with sufficient propellant reserve to itself ascend to lunar orbit, or carries a smaller ascent stage as payload. The ascending vehicle performs rendezvous with the orbiting Elytra, which uses its remaining propellant to return any captured samples to Earth (pictured).



Many of the key challenges of these architectures are already being proven on funded missions, not the least of which is landing. If Firefly were to forego commercial payloads, the Elytra stage flying as part of the CS-3 task order would complete its portion of the mission in an elliptical lunar frozen orbit with sufficient propellant reserve to return a sample to Earth. There is no architectural mandate that all Elytra's launch on the same vehicle. The cadence of CLPS and commercial missions may well create alternative opportunities to extend the missions of orbiting assets. Key remaining challenges to be demonstrated include rendezvous (which has much overlap with landing capability) and re-entry survival.

Summary: Diverse sample return is achievable in the near-term using the building blocks prepared in support of the CLPS program.



Inorganic and ductile thermoelectric materials for development of lightweight and efficient thermal blankets. B. Poudel[1], Y. Zhang[1], and N. S. Prasad[2] [1]Department of Materials Science and Engineering, Penn State University, [2] Remote Sensing Branch, NASA Langley Research Center, (Contact: narasimha.s.prasad@nasa.gov)

Introduction: Surviving lunar winters is a challenging endeavor for long-duration surface exploration[1]. Several thermal protection technologies including advanced radio isotopes and advanced materials have been proposed to survive extreme conditions[2]. Establishing continuing presence requires surviving lunar nights effectively and elegantly.

In this talk, we will discuss the thermal management of space vehicles using ductile and inorganic thermoelectric materials. Being solid-state with no moving parts, thermoelectric devices are extremely reliable, noise-free, and low-maintenance devices, which provide consistent cooling and heating. Flexibility, weight, and thermoelectric performance are key parameters in developing efficient thermal blanket for thermal management solutions. With the recent discovery of ductile and inorganic thermoelectric alloys, it opens the door for developing efficient and flexible thermal management solutions[3-5]. Traditional approaches using organic thermoelectric materials suffer from low materials figure-of-merit (zT) thereby limiting their applications. Silver chalcogenide based ductile thermoelectric alloys have shown exceptional ductility and excellent thermoelectric performance. In our lab, we have successfully developed the ductile silver chalcogenide alloys and tested the mechanical properties. Not only, these materials are shown to exhibit excellent zT, they can handle more than 50% strain without a crack. These materials can be made into a stand-alone thick film with thickness as small as 25 microns. These materials can be integrated into flexible and lightweight thermal blanket development (See Figures 1-2). The proposed thermal management solution is a transformational method for localized and conformal needs of electronics thermal management, which uses lightweight and flexible high-performance thermoelectric materials..

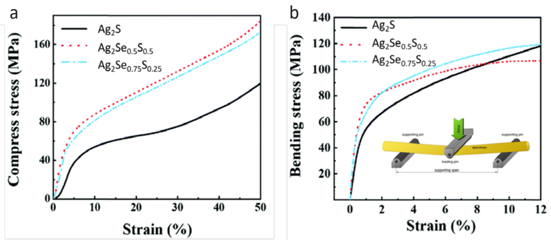


Figure 1. Room temperature strain–stress curves for (c) compressing tests and (d) bending tests of $Ag_2S_{1-x}Se_x$ (x = 0, 0.5, and 0.75). The insets in (d) show the schematic illustration of three point bend test adopted in this work.

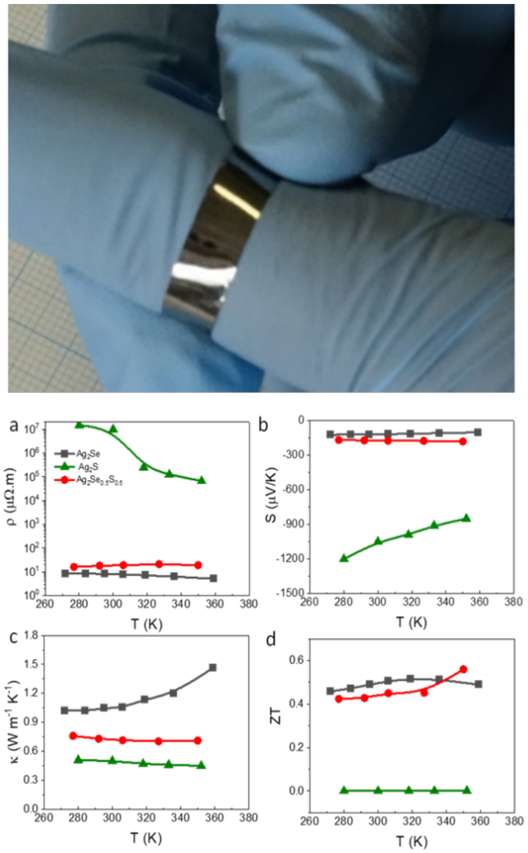


Figure 2. Top figure shows the flexibility of the 25 micron flim of the material and bottom figures summarize the thermoelectric properties.

References:

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[5] Xun Shi, hongyi Chen, et al., (2018) Nature Materials 17, 421–426.

ISRU Pilot Excavator – Advanced Autonomy Chris Rampolla[1], Alexander Pletta[1], Aidan Earley[1], Aleksandr Dobrev[1] and Benjamin Younes[1], Astrobotic Technology Inc, 1016 N Lincoln Ave, Pittsburgh, PA 15233. (chris.rampolla@astrobotic.com)

Introduction: The In-Situ Resource Utilization (ISRU) Pilot Excavator (IPEx) is a robotic spacecraft funded through the Space Technology Mission Directorate (STMD) Game Changing Development (GCD). IPEx is a forward-looking excavation platform designed to precisely cut, transport, and deposit regolith on the lunar surface. Robust and versatile robotic lunar excavation systems such as IPEx will be important to early efforts in establishing permanent lunar surface infrastructure. The breadth of its functionality necessitates nearly full system autonomy within the bounds of a dedicated area of operation. This contained operational area greatly contrasts with previous planetary autonomy approaches focused on vast traversal, which presents new challenges in the domain of planetary robotics. Astrobotic, in partnership with NASA Kennedy Space Center, is developing both avionics and autonomy for the IPEx platform, extending the capabilities of KSC's original Autodig development [1].

Concept of Operations: The Concept of Operations (ConOps) targets regions within the High Lunar Southern Latitudes (>85°S). Following deployment, the IPEx rover will perform checkout and calibration routines and then begin mission operations. The rover will first drive radially away from the lander and carefully traverse the edge of the operational zone, defined notionally as the circular region with lander-at-center and having a radius of ~65m. During the initial traverse, a map of the terrain and potential hazards is continually generated and refined. Viable dig and dump zones – areas where regolith will be cut and later deposited, respectively – are selected by ground operators using data products from the rover. With mapping completed, IPEx autonomously navigates and traverses between waypoints, avoids hazards via path planning and online methods, and carries out regolith excavation, transport, and deposition phases.

Autonomy Goals: The IPEx autonomy design supports lean, continuous operation of the rover to maximize mission performance objectives. The current development focus is the design of autonomous subsystems combining waypoint-guided traversal with Autodig excavation capabilities [1]. These subsystems incorporate robust perception, mapping, localization, and control algorithms that safely guide IPEx throughout the operating zone. To accomplish this level of sustained operation, autonomy subsystems will require precision and accuracy unprecedented in prior planetary robotic missions. In addition, the lunar south pole presents a unique challenge due to the extreme illumination conditions resulting from the low elevation angle of the sun against the local horizon. Finally, autonomy subsystems must remain functional within a landscape continually altered by excavation activities while also mitigating effects of regolith lofted upward through those same activities.

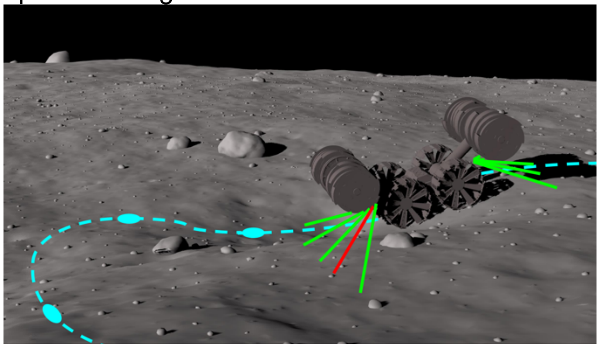


Figure 1. Simulated IPEx regolith excavation rover autonomously traversing terrain

Conclusion: NASA KSC and Astrobotic are presently working jointly to establish a system baseline for IPEx. This baseline will be a key data point for robotic lunar excavation and South Pole missions with high levels of autonomy required. Targeted testing in physical environments with simulated polar conditions will identify areas for further refinement and development. The current development stage culminates in a terrestrial demonstration spanning a full lunar day cycle to prove and evaluate system performance. Insights from data and testing will guide programmatic and technical iterations as IPEx advances and hones its capabilities.

References:

[1] B. C. Buckles, J. M. Schuler, A. J. Nick, J. D. Smith, T. J. Muller (2022) *Space Resources Roundtable, XXII Meeting*, ISRU Pilot Excavator - Development of Autonomous Excavation Algorithms

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

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

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

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

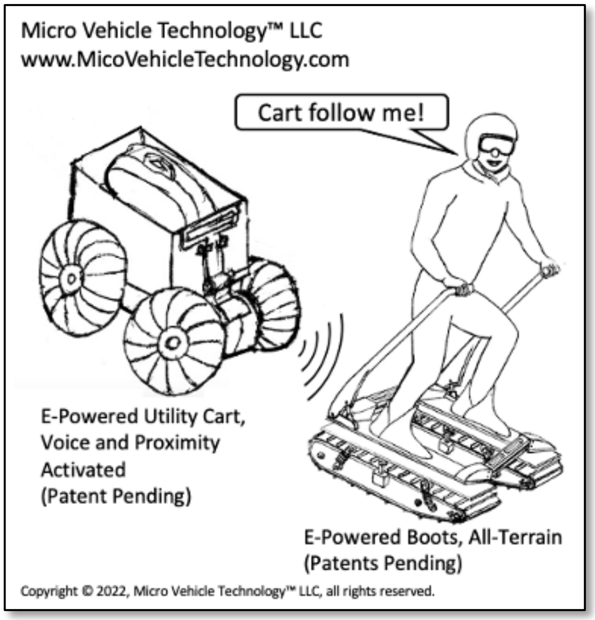
The Innovation:

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

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

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

- Launch weight may be much less for multiple personal Micro Vehicles™ compared to a single multi-passenger rover.
- Multiple personal Micro Vehicles™ may be easier to package, distribute weight, and subsequently deploy from a surface lander or cargo vehicle compared to a single multi-passenger rover.
- Powered Boots Micro Vehicles™ reduce the need for astronauts to walk and sit, thus mitigate health and constricted spacesuit concerns.
- Use of Powered Boots Micro Vehicles™ will cut out much time from the already planned Artemis III xEVA Con Ops walking range or may allow additional activity and greater exploration distances than currently planned.
- Multi-passenger rovers can be equipped with Micro Vehicles™, therefore, in case of rover failure, mitigate a lengthy and physically exhausting walk back scenario.
- With each astronaut using their own personal Micro Vehicle™ like ants, surface travel routes, colonization, and operations can be expedited and optimized for efficiency and fault tolerance.



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

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

Towards a Comprehensive Framework: Defining Parameters and Constraints for Sustaining a Prolonged Lunar Presence. Samalis Santini de León[1], Milena Graziano[1], Karen Stockstill-Cahill[1] , and Andrew Gerger[1]Johns Hopkins Applied Physics Laboratory. (Contact: samalis.santini.de.leon@jhuapl.edu)

Introduction: Establishing a sustained presence on the lunar surface demands a comprehensive approach that addresses the intricate interplay between technical excellence, economic viability, and resiliency. The technical dimension involves the design, integration, and qualification of hardware while integrating redundancy, adaptability, and contingency planning to ensure system robustness. Economic considerations require a meticulous evaluation of cost-effectiveness, potential revenue streams, and sustainable financial models, all within the context of a resilient architecture. Resiliency pervades both technical and economic factors, encouraging adaptability to unexpected disruptions and the ability to recover without compromising mission continuity.

In conjunction with the Lunnar Surface Innovation innitative (LSII) and the consortim (LSIC), this work aims to delve into the critical task of defining the parameters and constraints necessary for an architecture that supports a prolonged lunar presence. Primarily focused on resiliency to the lunar environment, we present an integration framework for requirements definition of lunar surface systems. The framework integrates technical specifications, economic considerations, and resiliency principles to ensure mission success in the face of uncertainties

A cornerstone of this framework lies in robust validation and verification strategies, ensuring that integrated requirements align with high-level objectives. These strategies enable the thorough testing and validation of systems under various scenarios, bolstering confidence in their ability to deliver on mission goals. Moreover, the framework places emphasis on integration and traceability, meticulously linking high-level objectives to stakeholder needs and technical specifications. This integration fosters alignment across disciplines and ensures that each requirement contributes coherently to the overarching mission objectives.

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Design and Hardware Progress on a Magnetically-Geared Actuator for Extremely Cold Lunar Environments. Justin J. Scheidler[1], Aaron, D. Anderson[1], Thomas F. Tallerico[1], George R. Harpster[2], Peter A. Hoge[2], Kyle R. Whitling[2], Jesse Hawk[2], Derek J. Quade[1], Michael D. Anderson[1], [1] NASA Glenn Research Center, 21000 Brookpark Rd, Cleveland, OH 44135, [2] HX5, LLC, 3000 Aerospace Parkway, Brook Park, OH 44142. (Contact: justin.j.scheidler@nasa.gov)

Introduction: Under the Motors for Dusty and Extremely Cold Environments (MDECE) Project, NASA Glenn Research Center is developing a magnetically-geared actuator for extremely cold space environments to avoid the wiring and significant efficiency penalty associated with heating grease-lubricated actuators as well as the stringent life and loading constraints imposed by dry film lubricated mechanical gears [1]. The heating penalty can be equivalent to up to a 90% efficiency reduction in permanently shadowed regions on the Moon [2]. This poster or presentation will summarize the progress made over the past 6-12 months on designing the fully-functional actuator and building a proof-of-concept actuator and testing it in an ambient environment.

Design Progress: A critical design review was successfully completed at the end of June 2023. This presentation will touch on the key highlights from that review in the areas of electromagnetic design and optimization, bearing optimization, thermal analysis, structural analysis, and mechanical design and manufacturing. The predicted technical performance measures of the actuator will be mentioned. The team is currently finishing some actions from the review and finalizing the drawing package in preparation for hardware procurement.

Hardware Progress: Despite some significant delays in receiving fabricated parts and magnetic subassemblies, progress was made in manufacturing and assembling a proof-of-concept version of both the actuator's magnetically-geared motor (Fig. 1) and the actuator's cycloidal-type output magnetic gear stage (Fig. 2) [3]. The presentation will mention key lessons learned to date from the fabrication, assembly, and testing of the proof of concept.

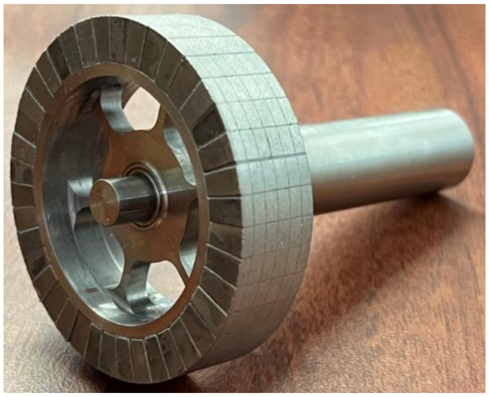

Figure 1: Sun gear for the proof-of-concept actuator's magnetically-geared motor.

Figure 2: Assembled prototype cycloidal magnetic gear.

References:

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An Optimization-Based Toolchain for Parametric Mechanism Design. A. Schepelmann, NASA Glenn Research Center, 21000 Brookpark Road, Cleveland, OH, 44135. (alexander.schepelmann@nasa.gov)

Design-Build-Test approaches for developing spaceflight hardware are prohibitively time and cost intensive and often lead to suboptimal mechanism designs. Approaches that couple machine learning and high-fidelity physics simulation could eliminate the need for hardware prototyping and dramatically accelerate the engineering design cycle, ultimately reducing cost. This work presents a modular NASA-developed toolchain to optimize hardware mechanisms in a virtual environment using numerical optimization and multi-body physics simulation.

The toolchain enables multi-objective optimization, generates parametric CAD files that can be further post-processed by an end user, and can be expanded to optimize full systems and non-mechanical parameters such as feedback control variables.

We demonstrate the toolchain through an independently verifiable design problem that optimizes wheel radius to achieve a desired linear velocity in a rigid-body physics environment when the wheel rotates at a constant angular speed, and then post-process the parametric CAD file of the optimal design generated by the tool before ultimately manufacturing it via 3D printing.

We end with a discussion of how the toolchain can incorporate other analysis tools, including finite element analysis, computational fluid dynamics, and granular media simulations.

Visible and Thermal Multiband Panoramic Imaging Systems for Lunar Exploration. R.N. Schindhelm[1], K. L. Donaldson Hanna[2], A. Dove[2], B. Denevi[4], P. Hayne[5], M. Sandford[1], J. Sunshine[3], R.A. Yingst[6], [1]Ball Aerospace, [2]University of Central Florida, [3]University of Maryland, [4]Johns Hopkins Applied Physics Laboratory, [5]University of Colorado, [6]Planetary Science Institute (Contact: Rebecca.schindhelm@ballaerospace.com)

Introduction: We present imaging systems for use in lunar rover exploration. A combined thermal/visible multiband panoramic imaging system has evolved from the In-space Validation of Earth Science Technologies (INVEST) and Lunar Surface Instrument and Technology Payloads (LSITP) programs, to be flown under the Payloads and Research Investigations on the Surface of the Moon (PRISM) program. In addition, with funding from the Development and Advancement of Lunar Instrumentation program, a high dynamic range camera is being developed to enhance science return in shadowed polar regions.

Lunar-VISE: The Lunar Vulkan Imaging and Spectroscopy Explorer (Lunar-VISE) determines the composition and rock type of the Gruithuisen domes, placing critical constraints on their formation mechanism. The 10-day science investigation uses straightforward rover and lander operations to collect surface spectral and imaging measurements at high spatial resolutions, for both pristine regolith and exposed boulders on a dome summit. These provide a critical link to existing orbital data sets, extending what we learn at Gruithuisen to other non-mare silicic spots, building an understanding of late-stage silicic volcanism on the Moon. Mature instruments on both the lander and rover minimize development and schedule risk. Lunar-VISE observations will be used, for the first time, to map composition and thermophysical surface properties with orbital spectral signatures and make in-situ gamma ray and neutron spectroscopy (GRNS) measurements within the Procellarum KREEP Terrane (PKT).

The Lunar-VISE Visible/Infrared Multiband Suite (LV-VIMS) combines two multispectral imaging instruments in a single enclosure: the VNIR Imaging Camera (LV-VIC) and Lunar-VISE Compact Infrared Imaging System (LV-CIRiS). The LV-VIC and LV-CIRiS are co-boresighted, rotating together on a common rotation stage, pointed forward, from the rover top. Images acquired by the two instruments at regular intervals during panoramic scans are assembled on the ground into gapless superimages in all bands. A full 180° scan takes less than 4 hours, including periodic LV-CIRiS calibration. Commands may also initiate scans over specified angular ranges for features of interest. The complete LV-VIMS image set spans 7 Vis/NIR and 4 TIR bands, and a FOV extending over a wide spatial range (~19°x180°).

Revelio High Dynamic Range Camera: Revelio is a high sensitivity VNIR camera that expands the range of imaging environments for landed or roving missions on the lunar surface. Shadowed regions appear in much greater contrast to sunlit regions on the lunar surface than on bodies with an atmosphere, an issue that is particularly problematic given that many of the highest priority lunar landing sites for science, exploration, and technology are in or near permanently shadowed regions (PSRs). Revelio helps solve this problem by making it possible to acquire high-spatial resolution, high-science-content images over a range of ambient illuminations – i.e., a high sensor dynamic range (>15,000). This range enables characterizing volatile deposits, identifying potential resources, measuring cratering rates, and carrying out other surface operations in scenes with shadowed regions without an external light source.

Revelio combines a flight heritage sensor with Ball's automatic gain and exposure control (AGEC) and pixel merging algorithms. A breadboard version has been demonstrated in the laboratory, and a point design exists for a potential flight prototype. Revelio uses a CMOS sensor that sends out high- and low- gain images in parallel for every frame. This is supplemented by AGEC algorithms, extending the dynamic range achievable in a single image to maximize signal to noise ratios (SNRs) in direct sunlight and in shadow (intrascene dynamic range > $2x10^8$). The sensor control electronics enable a low power, compact camera, and the electronics and packaging draw flight heritage from Ball's Geostationary Earth Orbit (GEO) Space Camera (BGSC). Through Internal Research and Development (IR&D), the Revelio breadboard system is at a Technology Readiness Level (TRL) of 4 with a clear path to TRL 6 through demonstration of a brassboard with engineering grade (same form/fit/function as flight) electronics parts and packaging in a relevant environment. The LV-VIMS instrument could be upgraded for polar missions to include Revelio instead of LV-VIC as the visible multiband imager for enhanced science return.

Lunar Dust Tolerant Electrical Contact and Connector development capable of 20,000 durability cycles. Ritch A. Selfridge, Senior Technology Engineer, Amphenol Aerospace. 191 Delaware Avenue, Sidney, NY 13838. (rselfridge@amphenol-aao.com)

Introduction: Electrical connectivity will be required between various devices on the lunar surface. Certain applications will require up to 20,000 engagement and separation cycles, such as docking stations for charging of robots/rovers, and interchangeable tools, batteries, and other devices. In the interest of minimizing size and weight while maximizing electrical conductivity, Amphenol has been developing and testing a lunar brush contact system which has been optimized to operate when contaminated with lunar dust.

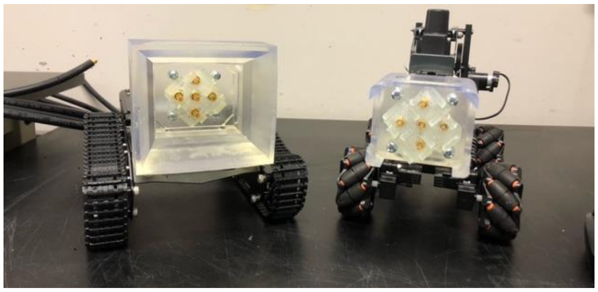


Figure 1: Amphenol 5 pole docking connectors mounted to remote-controlled vehicles.

Testing: A test apparatus has been developed that provides an accurate measurement of contact resistance versus contact engagement for every durability engagement and separation cycle.

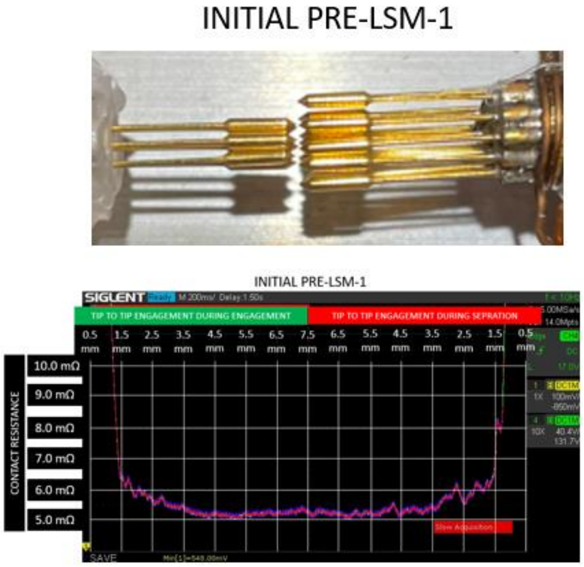


Figure 2. Amphenol's lunar brush contact prototypes and resistance vs engagement plot.

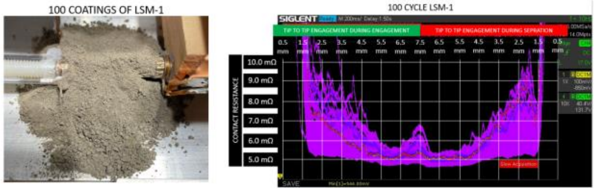


Figure 3. Amphenol's lunar brush contact prototype immersed in LSM-1 for cycles 25-100, and the cumulative resistance versus engagement plot for the 100 cycles.

Lunar brush contact designs (patent pending) have been evaluated through 8,800 durability cycles, with LSM-1 simulant applied directly to the contacts between every cycle.

Figure 4. Amphenol's lunar brush contact prototype after 2,500 durability cycles (patent pending).

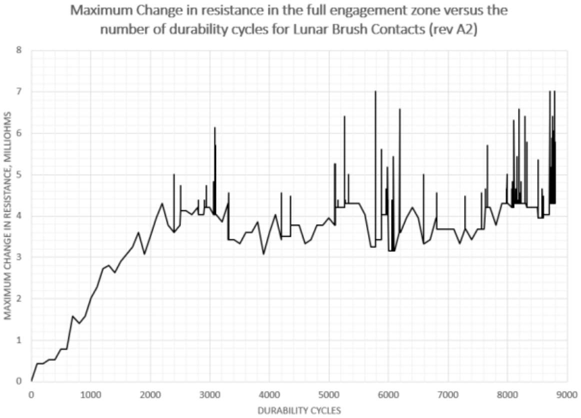


Figure 5. Maximum change in contact resistance versus the number of durability cycles. Spikes indicate single events that reset on subsequent durability cycles.

Additional testing is underway towards achieving 20,000 durability cycles.

In Situ Resource Utilization of Lunar Minerals Through Biomining Extraction Processes. E. Seto[1], K. Bywaters [1], N. Bouey[1] and K. Zacny[1], [1]Honeybee Robotics, 2408 Lincoln Ave, Altadena, C 91001. (Contact: epseto@honeybeerobotics.com)

Introduction: Moon offers minerals resources including silicon and aluminum (Table. 1). Biomining, the process of using microorganisms to extract metals of economic interest from rocks and regolith, offers an attractive method for making in situ resource utilization (ISRU) of Lunar minerals possible. As a part of microbial metabolism, microorganisms produce organic acids, and these can be used to leach metals in the biomining process. Biomining is currently being used, on Earth, in the mining industry to extract Cu, Al, Fe, and Au and obviate the requirement for toxic chemicals.

Table 1. Composition of a lunar mare sample 10017 [1].

Element	Lunar Sample 10017, weight %
Oxygen	40.7
Silicon	19.6
Aluminum	4.4
Iron	14.6
Calcium	8.2
Magnesium	4.8
Sodium	0.347
Potassium	0.206
Titanium	7
Manganese	0.148

European Space Agency (ESA)'s European Programme for LIfe and Physical Sciences in Space (ELIPS) project BioRock, investigated the behavior of microbes in contact with particles in altered gravity regimens on the International Space Station (ISS) to evaluate if microbial-supported bioproduction and life support systems can be effectively performed in space. In BioRock, microorganisms were dried on rock samples and then rehydrated once on the ISS. The microorganisms were then allowed to grow and extract elements from the rocks. BioRock found no significant differences in the microorganism growth between different gravity regimes [2].

Considering the BioRock experimental results and the mineral resources available on the Lunar surface, we propose using biomining as a method for Lunar ISRU.

Lunar Operational Scenario: Biomining the Lunar surface would be a straightforward process, very similar to the procedures used on Earth. Regolith would be mixed with microorganisms and nutrients, then allowed incubated for 1-5 days (depending on the organism and culturing conditions) to provide time for the microorganisms to extract metals into solution. During this period, culturing conditions, such as pH, temperature, mixing, would need to be maintained. Metals would then be extracted from the solution using conventional methods (e.g., electrowinning or precipitate).

Lunar Regolith Simulant Experiments: To investigate the bioleaching efficiencies of different stains and evaluate the production potential of aluminum extracted from Lunar regolith simulants, using microorganisms, the following experimentation is conducted.

Aspergillus foetidus, species of fungus, and *Acidithiobacillus ferrooxidans*, an acidophilic and chemolithoautotrophic bacterium, were selected. Both organisms are known for effective metal solubilization. Cultures will be grown in media containing Lunar Highland Simulant (LHS-1). Over the culturing duration, glucose consumption and organic acids (citric acid in *Aspergillus foetidus* cultures and sulfuric acid in *Acidithiobacillus ferrooxidans* cultures) production will be quantified using high performance liquid chromatography (HPLC) to investigate the corresponding bioleaching efficiencies. Inductively coupled plasma mass spectrometry (ICP-MS) will be used for Al analysis of culturing media over the duration of the experiments to determine production rates. Scanning electron microscope (SEM) images will also be taken to evaluate any changes in the morphology of the simulant.

Conclusion: From these experiments we will quantify the production rates of Al from Lunar simulate using microorganisms. These data will feed into an analysis of the feasibility of employing biomining as a strategy for ISRU of Lunar materials.

References: [1] Wänke, H., et al. (1970) *Lunar and Planetary Science Conference Proceedings.* Vol. 1. [2] Santomartino, R., et al. (2020) *Frontiers in Microbiology* 11: 579156.

Ionic Liquid-Facilitated Extraction of Metals and Oxygen from Lunar Regolith.

N. B. Singer[1], Z. Tanaka[1], and N. Netzer[1,2] [1]Diatomic Space Incorporated (Contact: noah@diatomicspace.com) [2]School of Arts and Sciences, Peru State College

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

Chemical Reactor: DSI is developing an ionic liquid-based chemical process for extracting metals and oxygen from lunar regolith, extending initial work completed at NASA Marshall [1]. DSI's work with choline-based ionic liquids have shown promising results, including the generation of gaseous oxygen and the plating of iron material from regolith slurry. Work is now proceeding to further characterize and scale this process for iron, investigate additional ionic liquids, and to extract additional target metals such as aluminum and titanium. This process is capable of processing both mare and highland regolith.

Ionic Liquids: Ionic liquids are a class of salts that are liquid below 100°C. Attractive properties of ionic liquids for spaceflight include low vapor pressure, high electrochemical stability, and high thermal stability. Ionic liquids are capable of digesting most metal oxides and silicates, including those found in lunar regolith, which facilitates in-situ oxygen production and metal byproduct extraction. Ionic liquids are tunable for specific applications and can be tailored to extract specific target metals from lunar regolith.

References:

[1] E. T. Fox, et al. (2018) *Ionic Liquid Facilitated Recovery of Metals and Oxygen from Regolith*

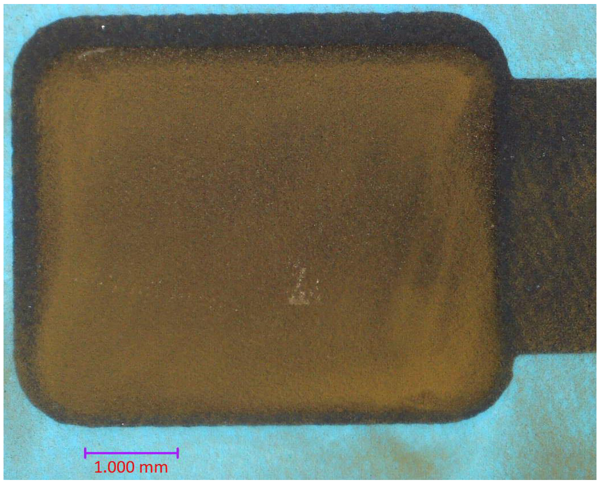


Figure 1: Carbon-based paper electrode plated with iron after 24 hours of electroplating from an ionic liquid-regolith slurry.

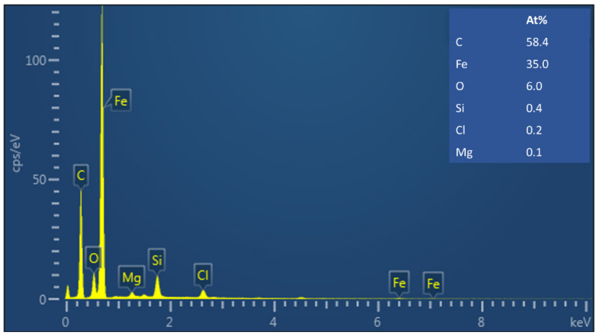


Figure 2: Energy-dispersive spectroscopy (EDS) data from electroplated material after 24 hours of electroplating from ionic liquid-regolith slurry. Data shows a high concentration of iron.

Campfires on the Moon: Surviving the lunar night with metal oxidation. J. Slavik[1] and T. Vazansky[1], [1]Astrobotic Propulsion and Test, 1752 Sabovich St, Mojave CA. (Contact: Jonathan.Slavik@astrobotic.com)

Introduction: Astrobotic has been developing the Nighttime Integrated Thermal any Electricity (NITE) system to allow scientific and commercial payloads to survive the lunar night. NITE will enable a new class of lunar night survival missions which are currently unserved by state-of-the-art battery and radioisotope heating solutions, with the goal of enabling rapid deployment of larger scale lunar infrastructure.

Figure 1: NITE heating subsystem during SBIR Phase II development

Previous and Current Contracts: Under an SBIR Phase II contract, this technology has been demonstrated to NASA TRL 4, and is currently being developed under a NASA GCD Tipping Point contract for TRL 6 demonstration. The end goal of these development programs is a lunar demonstration mission in the late 2020's to enable support for upcoming CLPS and Artemis missions [1].

Technology Development: NITE leverages an exothermic metal oxidation reaction to release thermal energy. The system recycles by-products from the oxidation and combines them with the stored oxidizer in a fuel cell to produce more heat and electricity. During efforts to simplify and lighten the fuel cell, a breakthrough was made in the functionalization of direct liquid fuel cells. Fuel cells with liquid reactants have long been conceptualized [2] but this application has yielded actual power production with realistic fuel/oxidizer combinations. Currently, NITE has a specific energy content more than 7 times greater than the latest battery technology, but unlike radioactive heating solutions, has precise control over heat/energy production (fully throttleable) and no serious regulatory hurdles based on the fuel and oxidizer selection.

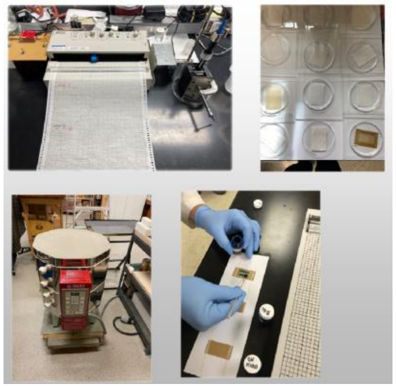


Figure 2: Direct Liquid Fuel Cell development

Applications: At its core, the goal of NITE is to enable lunar exploration missions for multiple lunar day-night cycles by providing the heat and power necessary to survive the lunar night. On first glance, a fuel/oxidizer based solution may seem counterintuitive for longer duration scientific, prospecting and observation missions. However, Astrobotic is focusing on the development of NITE as a component within a broader lunar architecture and suite of technologies. By leveraging the rapid deployablity afforded by a self-contained lunar heat and power system, NITE can be used to support the rapid deployment of larger scale lunar infrastructure like solar installations, surface fission power, and communications equipment. Once a base is established with this longer term infrastructure, NITE may still be used as a 'portable generator' in the construction of future outposts outside the range of an existing lunar grid.

References:

[1] Slavik J, Vazansky T, Kuhns M., Metal Oxidation Warming System to Provide Thermal and Electrical Power for Surviving Lunar Nights (2022), ASCE Earth and Space [2] B.C. Ong, S.K. Kamarudin, S. Basri, Direct liquid fuel cells: A review (2017), International Journal of Hydrogen Energy

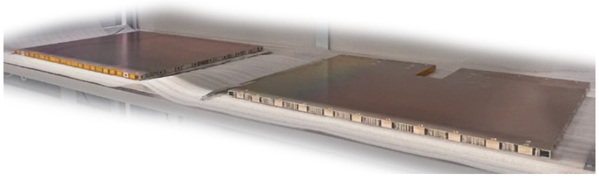
Passive Thermal Management System of Autonomous/Semi-Autonomous Rover for Lunar Shadow Survival.

Ryan Spangler[1], Jimmy Hughes[1], Joshua Smay[1], and Calin Tarau[1], [1]Advanced Cooling Technologies, Inc. 1046 New Holland Ave., Lancaster PA 17601 (Contact: Ryan.Spangler@1-ACT.com)

Introduction: A passive thermal control system has been developed in support of missions to the lunar surface. One such mission, NASA's Volatiles Investigating Polar Exploration Rover (VIPER), is a flagship mission planned to touchdown on the lunar surface in late 2024. VIPER will evaluate the permanently shadowed regions/craters of the southern pole of the lunar surface in search of water ice that could eventually be harvested to sustain human exploration on the Moon, Mars and beyond. To enable the success of this mission and similar missions, a novel thermal management system – capable of dissipating a high heat load when roaming or conducting science and minimizing heat leak away from the rover when dormant or in a permanently shadowed region – has been developed by ACT. This was achieved by using heat transfer technologies/components like Constant Conductance Heat Pipes (CCHPs) embedded into honeycomb panel structures, externally-mounted CCHPs, and Loop Heat Pipes (LHPs) with passive Thermal Control Valves (TCVs). This poster will seek to describe the utilization and functional purpose of each technology employed.

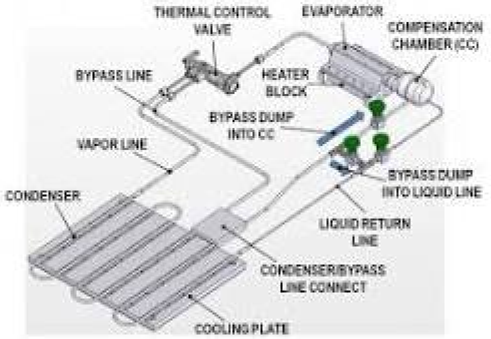
Constant Conductance Heat Pipes for High Effective Thermal Conductance: CCHPs are widely renowned for their ability to reliably transfer significant amounts of thermal energy with low temperature rise penalty. To manage the significant waste heat generated during roaming and science phases of the mission, CCHPs are used in several critical locations/contexts:

- Embedded in honeycomb structure: CCHPs are assembled within the honeycomb panels that comprise the electronics enclosure. This is the enclosure that houses and holds the many critical electronics required to complete the ConOps of the mission. Waste heat from the various electronics are gathered from disparate locations and carried to a single location for dissipation to the radiator panels. An image of heat pipe embedded heat spreaders is shown below.



- Directly attached to several instruments located outside the serenity of the electronics enclosure. These CCHPs carry the waste heat from the outboard instruments to the LHPs (with TCVs) that further transport the heat to the radiator panels for dissipation.

Loop Heat Pipes with Thermal Control Valve: The LHP with integrated TCV was selected as the technology to be the thermal link between the warm box (with temperature-sensitive electronics) and the radiator panels for waste heat dissipation. LHPs are commonly used in spaceflight thermal control due to their ability to passively transport large amounts of waste heat over long distances with a minimum temperature difference. The operational set point of LHPs is typically controlled by actively heating the cold biased compensation chamber. The current solution uses the novel approach of integrating a thermal control valve (TCV) that passively controls the vapor flow direction to either the condenser or directly to the compensation chamber or both. This novel approach eliminates the heat load required by the classical heating of the compensation chamber, and, therefore, minimizes the survival power (energy required to maintain the minimum survival temperature of the payload). An image of a LHP with TCV is shown below.



Vacuum Sealable Container (VSC) And Astronaut Lunar Drill (ALD) For Artemis

L. Stolov[1], K. Zacny[1], J. Spring[1], A. Grossman[1], K. Bywaters[1], T. Mathison[1], M. McCormick[1], R. Margulieux[1], S. O'Brien[1], C. Chen[1], L. Sanasarian[1], P. Chu[1], M. Fountas[1], A. Hood[2], C. Yamasaki[2],
[1]Honeybee Robotics (kazacny@honeybeerobotics.com), [2]NASA Johnson Spaceflight Center (JSC)

Introduction: NASA's Artemis Program is planning to land astronauts on the Moon for Artemis III and beyond. The astronauts will utilize a suite of new geology tools to conduct science on the lunar. Honeybee Robotics has been working with NASA JSC to develop a new Astronaut Lunar Drill (ALD) and new Vacuum Sealable Container (VSC) to enable sample return of sealed core samples from the lunar south pole.

Vacuum Sealable Container: The VSC is designed for astronauts to hermetically seal a core sample on the lunar south pole for return to Earth. The Apollo missions to the Moon had several kinds of Sealable Containers which brought back lunar samples for analysis. These samples are still being analyzed, fifty years later. The VSC requirements are different than for the Apollo containers and as such, new development was required. One major difference between Artemis samples and those from Apollo is the desire to bring a higher content of volatiles which is expected to be part of the regolith on the lunar south pole. The VSC is designed to withstand a high-pressure differential caused by sublimating volatiles, as well as avoid sample contamination from careful material selection. The VSC design is the result of requirements derivation, trade studies, and breadboarding. Functional prototypes for the VSC were assembled and underwent human factors testing and helium leak rate testing in vacuum.

Astronaut Lunar Drill: The ALD is designed to be a multi-functional platform for lunar sample acquisition. The system consists primarily of a rotary-percussive drill head, a linear stage, and drill stems, all designed for use by astronauts. The main functionality of the ALD is Deep Core Regolith Drilling, which can capture regolith cores up to 3 meters below the surface. Additional functionality includes Surface Rock Coring (SRC), which allows collection of shallow rock cores, and GeoTech Tools (GTT), which performs geotechnical measurements of the lunar surface with a static cone penetrometer and shear vane. The drill can also be used as a power tool for construction activities. Honeybee has developed a design for the ALD supported by requirements derivation, trade studies, and breadboarding. The design builds on lessons learned from the Apollo Lunar Surface Drill (ALSD), as well as Honeybee's long history of mechanized sample acquisition devices for space [1]. The drill head is designed to have decoupled rotary and percussion subsystems to allow for maximum battery life and reduced fatigue on the crewmember. The drill head mounts to a linear stage to improve drilling efficiency, simplify the drilling process for astronauts, and aid in the extraction of deep cores, which was a problem encountered during Apollo. The ALD is removable from the stand to allow crewmembers to collect surface rock cores from large boulders. This functionality utilizes Honeybee's Eccentric Tube Core Breakoff technology to collect and retain rock core samples [2]. Bringing back rock cores samples instead of full rocks allows for a wider variety of samples to be returned to Earth and puts them in an engineered form factor for sealing and analysis.

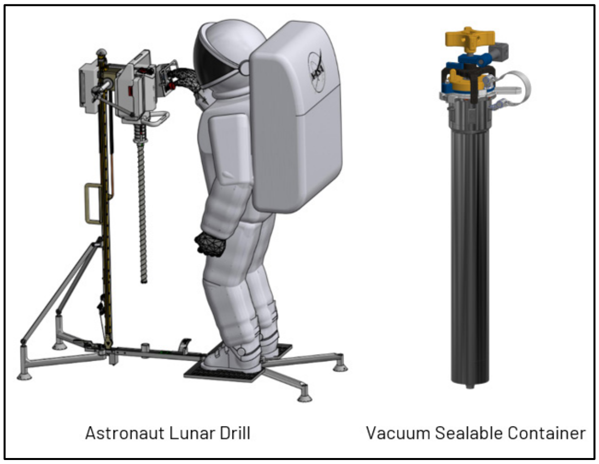


Figure 1. CAD images of Astronaut Lunar Drill and Vacuum Sealable Container (not to scale).

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Vacuum and Atmospheric Lunar Simulant Behavior and Geotechnical properties.

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Introduction: The return to the lunar surface and establishment of sustainable lunar infrastructure and commercial operations will require continuous interaction with the lunar surface material: regolith. Lunar operations will require excavation, handling and processing the regolith into structures and processed materials. To properly design these required systems that will have to operate for long times without maintenance in the harsh lunar environment it is crucial to understand the regolith properties and behavior. Most testing occurs under atmospheric conditions since no vacuum compatible test apparatus exists in regular soil mechanics labs. It is crucial to understand what (if any) differences there are in behavior when there is air in between the regolith simulant particles and when there is not. Michigan Technological University's Planetary Surface Technology Development Lab has developed vacuum compatible test equipment for testing lunar simulant behavior in vacuum conditions. Tests for direct shear, compaction, regolith transfer, hopper flow, (icy) regolith thermal testing and long term wear testing, were all conducted under atmospheric and vacuum conditions to see the differences and understand the behavior. Other tests like triaxial testing and permeability testing were done under atmospheric conditions to determine other relevant properties such as permability.

Direct Shear: A direct shear device was designed and built to test lunar simulant under vacuum conditions. A special sample preparation device is included which loads and prepares the sample in vacuum so no air is trapped in the pores. Tests were performed at different relative densities (40%-90%) to measure apparent cohesion and internal friction angle.

Compaction: Compaction of lunar regolith is required for construction. Various methods of compaction (vibration from top, with pins and with surface pressure plate) were performed and up to 90% relative density was achieved.

Regolith Transfer: Regolith transfer using a screw conveyor, piston conveyor and vibratory conveyor was compared and similar power levels were observed, but less dust contamination occurred in vacuum conditions.

Hopper Flow: Various hopper geometries made with polycarbonate were tested and it was found that in vacuum, hopper flow was up to 17 times faster than in atmosphere. This is being further investigated but is suspected to be due to the fine particle motion resistance in air.

Icy Regolith Thermal Testing: A test setup was created to measure the thermal properties of cemented and discrete (icy) regolith simulant under (cryogenic) vacuum conditions with various percentages of ice content. This allows more accurate modeling of thermal behavior of dry and icy regolith simulant.

Long Term Wear Testing: An standard ASTM G65 abrasion test apparatus was developed for cryogenic vacuum testing. This allows simultaneous testing of three cryogenically cooled material samples to be abrasion tested with lunar simulant under vacuum conditions. In addition, a 15 day non-stop vacuum regolith transfer test was conducted by positioning two screw conveyors in an X orientation so the regolith feeds from one into the other in an infinite loop. Wear was measured before and after as well as power during the test. A clear polishing and measurable wear gradient was measured on the screws from the bottom where regolith would enter and the top where coverage of regolith was much less.

Triaxial and Permeability Testing: Some properties could not be tested under vacuum conditions such as permeability or the more complex triaxial test. Permeability was found to be less than silt and in the high clay range. The simulant used was MTU-LHT-1A which is an in-house created lunar simulant consisting of a mixture of Anorthite in the form of Greenspar 90 and 250 as well as crushed basaltic scoria to create a particle size distribution matching the Apollo lunar highland data.

Additional testing: CBR and cone penetrometer testing was done in atmospheric testing to determine bearing strength and get regolith geotechnical properties down to 1m depth. The CBR testing will be repeated in the vacuum chamber in the future once the equipment is complete.

Watts on the Moon and Break the Ice Lunar Challenge Experiences. P. J. van Susante[1], M.C. Guadagno[1], B. Wiegand[1], C. Carey[1], R. Austerberry[1], H. McGillivray, P. Bradshaw, and G. Johnson[1], [1]Michigan Technological University Planetary Surface Technology Development Lab, 1400 Townsend Dr, Houghton, MI, 49931, (Contact: pjvansus@mtu.edu)

Introduction: The return to the lunar surface and establishment of sustainable lunar infrastructure and commercial operations will require continuous interaction with the lunar surface material: regolith. Lunar operations will require power and any ISRU/processing will require excavation. An initial target for resource gathering is water ice that may be found in the lunar Permanently shaded craters (PSRs). Technologies to get power down into the PSRs and excavating the icy regolith is of great interest to NASA. To get many ideas for these topics NASA has organized two Centennial Challenges, the Watts on the Moon Challenge (WotM) and the Break the Ice Lunar Challenge (BTIL). The Michigan Technological University Planetary Surface Technology Development Lab (MTU PSTDL) is participating in both and has proceeded to Phase 2, level 2 of the BTIL Challenge and final Phase 2, level 2 of the WotM Challenge. Technology performance for both will be discussed.

WoTM Challenge: The goal for the WoTM Challenge is to deliver power to a NASA specified load totalling 5500 Wh with a given profile over time during a period of no power generation. During the 6-8 hour power generation, the NASA load needs to be supplied and the enery storage recharged. The technology proposed and tested by the MTU PSTDL consists of a super conducting tether, power conversion system and a battery. During sub-system testing, our superconducting cable, power converters, battery and thermal systems were all tested in a thermal vacuum chamber.

BTIL Challenge: The goal for the BTIL Challenge is to excavate 800k/day of a Controlled Low Strength Material (CLSM), which is a weak concrete, for 15 days straight for a total of 12,000 kg. Between excavation and delivery a distance of 500m has to be driven over a lunar landscape. MTU PSTDL developed PRIMROSE (acronym), a 332 kg robot that excavates the CLSM using a trencher and stores the up to 260 kg excavated material in a hopper. Once full, PRIMROSE traverses the 500m on its 4 independently steerable wheels over a bed of lunar regolith simulant. Over the 15 day durability test with PRIMROSE in the test setup, many lessons were learned about the designed system. X maintenance events had to be carried out during the 15 day durability demonstration test. 3000 kg of CLSM was collected (roughly 200 kg/day) and 30 km of distance was traversed on the regolith simulant. Since the regolith simulant bed was only xm long, PRIMROSE traversed the same section 3000 times. After some time, drive ruts formed that needed filling in. To this end a small plow was constructed from spare material and some of the regolith simulant in the center between the ruts was redistributed into the ruts and thus ‘road repair’ had taken place. On occasion, due to too heavy of a load, PRIMROSE would get stuck and the road required some careful driving to repair the holes that the wheels dug. An effective manner of doing so was driving close to the holes so they partially collapsed and then doing the same on the other side and then carefully driving over the filled hole to compact the material so it would be safe for driving again. Occasionally, the ability of PRIMROSE to lift individual wheels would come in handy to get out of a stuck position or get over an obstacle, like a berm that was formed by driving, then stopping and driving again. Small amounts of regolith would pile up after each direction drive but over time this added up to a significant pile. The scraper blade / plow was used to redistribute some of that regolith simulant back to the ruts and partially refill them. Many lessons were learned and a list of improvements for Phase 2, Level 3 has been prepared so that the system production rate would be increased to the maximum possible amount. Larger wheels will be implemented to easy traverses and minimize getting stuck.

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Figure 1: PRIMROSE after 30km driving on-lunar simulant

High Performance Heat Pipe Design, Manufacturing, and Testing. Jurie J van Wyk[1] and Johnny Torros[2], [1]Westinghouse Electric Pty,ltd, vanwykjj@westinghouse.com, , [21]Westinghouse Electric Pty,ltd, johnny.torres@westinghouse.com. (Contact: email address of lead author/primary contact)

Abstract: *The Westinghouse Electric Company LLC (Westinghouse) maintains its commitment to developing the eVinci^{TM} Micro Reactor, which embraces the application of alkali metal heat pipes. The eVinci^{TM} Micro Reactor utilizes a large array of alkali metal heat pipes to transfer heat from the reactor to a power conversion system. Westinghouse continues to reinforce the versatility of heat pipe-based reactor technology by developing proprietary manufacturing heat pipes that undergo strict quality-controlled techniques while also enabling rapid development. The high-quality manufacturing procedures entails fabrication in inert environments and requires stringent cleaning. This leads to reliable long-term performance of the heat pipes at high temperature environments. Westinghouse promotes the success of these processes, and the heat pipe technology has set performance records during long-term testing.*

The heat pipe design employs high heat transfer efficiency of liquid metal phase change and providing a high primary coolant system with no moving parts, ideal for space applications. The eVinci^{TM} Micro Reactor heat pipe design benefits include, great simplification of the system, operations with unparalleled reliability, eliminates significant and single point failure modes, eliminates risk from high system pressures, reduce mass, and enables prototypic life testing at operating temperatures.

Keywords: Heat Pipe, Micro Reactor, Design

Introduction:

Nuclear Energy – From Earth into Space. Jurie J van Wyk[1] and Johnny Torros[2], [1]Westinghouse Electric Pty,ltd, vanwykjj@westinghouse.com, , [21]Westinghouse Electric Pty,ltd, johnny.torres@westinghouse.com. (Contact: email address of lead author/primary contact)

Abstract: *Since 2015, the Westinghouse Electric Company LLC (Westinghouse) has been developing the heat pipe nuclear micro-reactor for terrestrial applications, and with the continuous growth into the space market. Westinghouse is committed to the development of heat pipe technology for commercial nuclear applications and has partnered with Los Alamos National Laboratory (LANL), which originated the heat pipes with their innovative programs: SNAP-10A, SP-100, kilo-power, and mega-power. The eVinci™ Micro Reactor is the viable commercial progression of the kilo-power and mega-power reactor designs.*

The Westinghouse eVinci™ Micro Reactor uses the same alkali metal heat pipe technology for primary heat transfer. Unlike Pressurized Water Reactor, the eVinci™ Micro-Reactor design leverages the heat pipe design as it takes the high heat transfer efficiency of liquid metal phase change, to transfer the high primary coolant system to the power conversion system with no moving parts. Furthermore, the commercial sustainability of the eVinci™ Micro Reactor technology is attributed to its ideal size. The size of the system permits easy transportation and low mass deployment. The heat pipe technology also enables safe transient response due to its isothermal behavior.

Keywords: Micro Reactor, Heat Pipe, Design

Introduction:

RENEST – Low Energy Additive Construction for the Moon and Mars.

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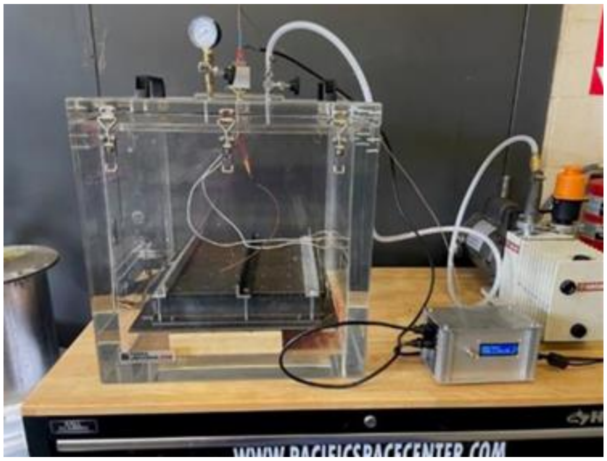
Introduction: NASA's return to the Moon with the Artemis program and the emergence of commercial lunar delivery are expected to increase the need for infrastructure to support larger and more frequent landings (and eventually launches) on the lunar surface. Landers and hoppers generate a rocket plume that can impinge on bare regolith, ejecting material at high velocity and excavating deep craters. Astrobotic is working to address these challenges by developing a unique in-situ construction material technology called RENEST (**R**efurbishment **E**nhanced **N**on-sintered **E**xtrudable **S**urface **T**echnology), which uses a low-energy technique to construct improved surfaces using in-situ resources. In addition to landing pads, RENEST can also be used to build roadways, footpaths, and vertical structures such as habitats. It can also be used to repair damaged materials and perform routine refurbishment to ensure infrastructure performs as needed in the harsh lunar environment.

Material: RENEST is a novel binder-regolith composite that can be cured into a hardened material in both vacuum and CO2 environments and is applied via an extrusion system. The curing process does not require additional energy input, making it highly desirable for use on the Moon, where power sources are limited. The composite is resistant to high temperatures, making it a useful material for landing pads. Additionally, the material can be used to fill joints between fabricated surfaces, and it can be used to refurbish sections that have been worn over time.



Prior and Development: Astrobotic has partnered with the Pacific International Space Center for Exploration Sciences (PISCES) program at University of Hawaii-Hilo to develop the RENEST technology. The team completed an SBIR Phase I project and will be starting Phase II in Q3 of 2023. In the Phase I effort, PISCES fabricated multiple RENEST pavers that were tested under Astrobotic's plume-surface interaction (PSI) rocket test stand. 12 pavers were fabricated by placing a mixture of the binder-regolith material into a mold that was then cured in a vacuum chamber. Conditions in the chamber were varied to replicate surface conditions for both the Moon and Mars. In addition to single pavers, grouted versions are also produced with two types of joint interfaces.

Hot Fire Testing: The fabricated pavers were tested under a relevant rocket exhaust plume using a 100 pound-force engine running on gaseous methane and oxygen. Each test was conducted at full thrust for two seconds with the engine height set at 0.2 meters above the pavers. After the initial hot fires, four of the pavers were refurbished using the same binder-regolith mixture. The RENEST pavers remained intact beneath the plume, including ones that were refurbished and tested multiple times. Structural testing also indicated that the pavers could support the weight of a lander on the Moon or Mars.

Upcoming Work: The Phase II SBIR effort will develop a full extruder system for RENEST, which will intake regolith and binder, mix the material internally, then extrude it directly onto the ground where it will cure. The system will be tested in a dirty thermal vacuum chamber in the HuskyWorks lab at Michigan Technological University, progressing development to TRL 5.

Exploring a Novel Approach for Lunar Agriculture: Optimizing Lunar Plant Growth with Halloysite Nanotubes through Innovative Modeling

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Introduction: This study is a pioneering effort to revolutionize Lunar Agriculture by harnessing cutting-edge techniques to elevate the potential of Heirloom-Cherry Tomatoes for cultivation and harvest on the lunar surface. Through the strategic application of Response Surface Methodology (RSM), this research aims to optimize the growth conditions essential for maximizing yields in the unique lunar environment. The investigation focuses on pivotal factors influencing growth yield. Traditional lunar agriculture faces numerous challenges, including limited resources, extreme temperature fluctuations, and a lack of nutrients. Our research addresses these challenges by investigating the integration of halloysite nanotubes, and natural aluminosilicate clay nanotubes as a growth-promoting agent. These nanotubes possess a high aspect ratio, large surface area, and cation exchange capacity, making them ideal candidates for enhancing nutrient and water retention in the regolith. In this study, we conducted a series of controlled environment experiments with varying concentrations of halloysite nanotubes. Growth parameters such as germination success, root elongation, shoot development, and nutrient uptake were meticulously analyzed. Our findings demonstrate that the incorporation of halloysite nanotubes positively influences these growth parameters, signifying their role in mitigating lunar agriculture challenges. The outcomes of rigorous experimentation unveil a precise set of optimal parameter Magnesium-Halloysite Nanotubes (Mg-HNTs) Concentration calibrated to 100 mg/L. Particularly noteworthy is the profound influence of Mg-HNT concentration on the growth process. Achieving an extraordinary Germination Percentage Yield of 98%, the study also assesses crucial physiological markers including Seedling Length (25.45 cm), Root/Shoot Ratio (2.71 cm), Seedling Vigor Index (SVI - 25.44%), Shoot Length Stress Tolerance Index (SLSI% - 158.29), and Root Length Stress Tolerance Index (RLSI% - 157.33). The alignment between predicted values and experimental results reinforces the efficacy of the response surface model, affirming its potential as a reliable tool for forecasting Heirloom-Cherry Tomato growth yields in optimal lunar conditions. This study not only demonstrates the feasibility of cultivating high-quality crops in space but also introduces a transformative approach to Lunar Agriculture through the integration of Halloysite Nanotubes. The strategic incorporation of Magnesium (Mg) HNTs not only enhances germination rates and percentages but also amplifies seedling vigor, augments nutrient assimilation efficiency, and bolsters stress tolerance levels. In conclusion, our study pioneers a novel approach to lunar agriculture by introducing halloysite nanotubes as growth-enhancing agents in lunar regolith. This research stands as a groundbreaking contribution to the field of Lunar Agriculture, showcasing the transformative impact of innovative methodologies and advanced materials like Halloysite Nanotubes. By pushing the boundaries of extraterrestrial cultivation, this study not only opens doors to future agricultural sustainability in space but also enriches our comprehension of the potential for life beyond Earth [1-5].

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Mitigation of Lunar Regolith Toxicity Using Halloysite Nanotubes: A Conceptual Approach for Lunar Soil Remediation

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Introduction: As humanity turns its attention towards sustained lunar exploration and potential habitation, the issue of lunar regolith toxicity emerges as a paramount concern. Lunar regolith, comprising a complex matrix of materials, harbors compounds that could pose risks to both human health and technological infrastructure. This study introduces an innovative remediation strategy, centered around the utilization of Halloysite nanotubes (HNTs), to alleviate lunar regolith toxicity and facilitate safe lunar activities. HNTs, natural nanomaterials with inherent hollow tubular structures, exhibit remarkable physicochemical properties that make them attractive candidates for environmental applications. This study proposes the utilization of HNTs to sequester and neutralize toxic species within the lunar regolith, thereby rendering the soil safer for human contact and sustainable resource utilization. The proposed approach involves a comprehensive methodology encompassing HNT extraction, characterization, modification, and integration into lunar regolith. Key objectives of this research include assessing the efficacy of HNTs in adsorbing toxic elements from simulated lunar regolith, evaluating the changes in physicochemical properties of lunar regolith after HNT treatment, and extrapolating the feasibility of large-scale implementation of this approach on the lunar surface. Additionally, the potential impacts of HNT incorporation on the mechanical and thermal properties of the regolith will be investigated to ensure the viability of proposed remediation techniques within the lunar environment. Successful implementation of the proposed approach could pave the way for the establishment of safe and habitable lunar bases, where regolith toxicity is effectively managed. In conclusion, this research offers a novel perspective on addressing the challenge of lunar regolith toxicity through the innovative use of HNTs. The findings and methodologies presented herein aim to stimulate discussions and collaborations within the lunar exploration community and contribute to the realization of long-term human presence on the Moon.

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Redefining Space Sustainability: A Broader Look at Sustainability Across the Space Industry. M. M. Violette[1] and B. M. Andrus[2], [1,2]The Aerospace Corporation, 2011 Crystal Dr, Arlington, VA 22202. (Contact: megan.fitch@aero.org)

Introduction: Space Sustainability, just like on Earth, is a multi-pronged approach to development that involves design, logistics, technology, policy, economics, equity, resource efficiency, and many more factors. The overuse of the word "sustainability" has led to various and vastly different definitions across the space industry, creating confusion and often clouding the broader picture. Through the lens of Space Sustainability, the space industry can ensure that future development on the lunar surface will be resource efficient, economically feasible, and socially inclusive.

With increasing sustainability discussions across many industries, there is mounting social and economic pressure for the government and private sector to change their processes and standard operating procedures to become more sustainable. The nascent plans for lunar surface development present a pivotal moment where sustainable practices can be written directly into the fundamentals of policies, regulations, materials choices, systems, architectures, and logistics. These sustainability plans could include topics such as resource management, end-of-life, waste management, interoperability for architectures, and even accessibility plans. Proactively implementing sustainable practices could prevent the costly rework needed to improve already-established, and highly-unsustainable systems, in the future.

NASA has already begun outlining the 63 Moon to Mars objectives [1], further pushing the need for sustainable measures in space. The industry must step up to help guide this process.

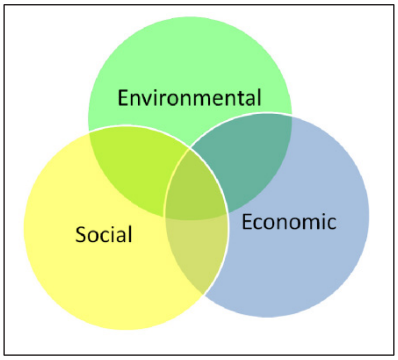

Figure 1 [2]

The three pillars of Sustainability:

1) Environmental: The pillar most often associated with "sustainability", has to do with anything related to the environment and how humanity interacts with it. In order to minimize the environmental impacts of the space industry, resource efficiency is key. Consideration should also be given for any impacts the space economy might have on the lunar and terrestrial environments.
2) Social: The norms that define interaction and governance between people- legally, ethically, and even culturally. This pillar is generally considered the least in sustainability discussions because of gray and subjective areas that require broader inputs from a wide range of individuals. In addition, the current legal framework lacks mention of sustainability and responsible management of in-space resources. In order to have a just and sustainable space industry, it will require that future space policy is inclusive of current and future participants in space exploration and lunar surface development.
3) Economic: This pillar considers the production and consumption of goods. To be the most cost effective, there must be consideration for the reusability of existing materials, creation of in-situ resources, and development of an in-space circular economy that makes use of by-products.

Conclusion: Sustainability is intertwined in each part of our lives and should equally be at the intersection of each aspect of lunar surface development, which will require input and cooperation from a diverse collection of groups across the industry.

Whether it's resource or operating efficiencies, ensuring a just and equitable space environment, or looking at the cost-effective future of space exploration; the space industry must consider how activities on the lunar surface will impact the space environment for decades to come.

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Efficient Truss Structures from Regolith Glass.

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(Contact: wainner@psicorp.com)

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

The project targets an end goal truss design of 5m length with triangular cross-section and aspect ratio ~50. Length and straightness target accuracy metrics of $1x10^{-4}$m and 1.3mm/m lend themselves to the construction of large orbital structures with high precision. Similar straightness requirements are imposed on the glass rods that make up the assembly. Truss strength objectives and strength of the regolith glass material dictates the allowable fineness of the rods that comprise it. However, varying lunar or orbital construction applications can call for different strength and shape requirements. The method will be flexible for producing parts and building blocks of different character.

The DARPA-funded project is still underway but close to completion by the LSIC Fall Meeting. The related poster or presentation will provide an update on progress and results and will demonstrate one or more exemplar trusses of 2m length, constructed of regolith simulant glass rods that are welded together to produce the (essentially node-free) construction. Molded regolith glass nodes are still anticipated, however, to enable the joining of multiple trusses together at their ends.

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

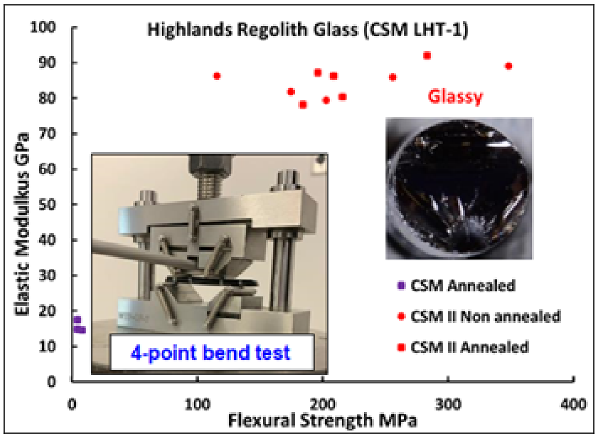

Figure 1. 4-point bend testing of regolith rod specimens. Inset pictures show the test apparatus with regolith rod & deflectometer in place, and cross-section of a sample at its failure surface.

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

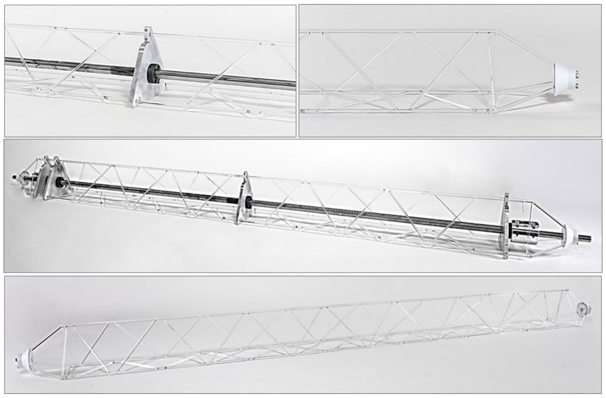

Figure 2. Photographs of the prototype 2m welded glass truss, buiit in borosilicate, with and without assembly jig in place.

Developing a Large-Scale Lunar Regolith Test Bin with Gravity Offload Capabilities.

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Introduction: The increasing interest in Lunar surface exploration is driving the development of new Lunar rovers and hardware. The demand for mineralogically accurate Lunar test beds is increasing alongside this development. A test bed with features such as gravity offload, drilling options, and different terrain variations would provide a resource for Lunar hardware testing on Earth. To further the availability of regolith test beds, the Exolith Lab at the University of Central Florida is developing a 100m^2 regolith bin offering the mentioned features and more.

With NASA's Artemis missions returning to the Lunar South Pole, regolith bins matching the characteristics of the Lunar Highlands are of increased importance. The Exolith Lab produces Lunar regolith simulants which approximate both the mineralogical and geotechnical characteristics of the Lunar Highlands (LHS-1) [1] and Lunar Mare (LMS-1) [2]. At Exolith, we believe it essential that both mineralogy and geotechnical characteristics are represented within a simulant. A variant of this simulant, LHS-2E, will be used inside the regolith bin that consists of a larger particle size distribution [3]. A significant amount (10-20%) of the regolith bin simulant will be between 1-2mm whereas typical LHS-1 is less than 1mm.

Design Considerations: Exolith's regolith bin will have a footprint of 10x10m and a depth of 1m providing ample room to perform drilling experiments. A 4ft tall retaining wall will be built to contain the ~130 tons of Lunar Highlands simulant. An essential design feature of the bin is the regolith simulant itself, which has an improved particle size distribution. The distribution of the new regolith simulant is more representative of the Lunar surface, with coarse Anorthosite and Basalt included. A larger particle size range provides a more inclusive representation of Lunar simulant and will be beneficial to researchers testing hardware within the regolith bin.

Located on a walkway bordering the regolith bin is the main personnel access point. This structure will act as a clean room, using negative pressure to keep any fine dust in the air from escaping the regolith bin. This clean room will also include space for donning personal protective equipment (PPE) before entering the bin. One side of the bin will also be turned into a roll-up door to allow large equipment to be inserted into the test bed.

Testing Features: A regolith bin with 100m^2 of usable space presents the opportunity for features not available elsewhere. Gravity offload is one feature that will be provided, allowing vehicles being tested to offload 5/6th of their Earth weight, mimicking lunar gravity. This will be done through the overhead gantry crane keeping a constant lifting force on the vehicle throughout its testing.

With a 1m depth and 100m^2 footprint, we will have the ability to set up hills within the bin that can be used for the testing of drills and other mining equipment. This will enable essential ISRU testing to be conducted within the regolith bin. Custom terraforming options will be available for customers, with the ability to create craters, hills, boulders, stratigraphy, and other structures. It will also be possible for us to create areas within the bin of different regolith simulant compositions.

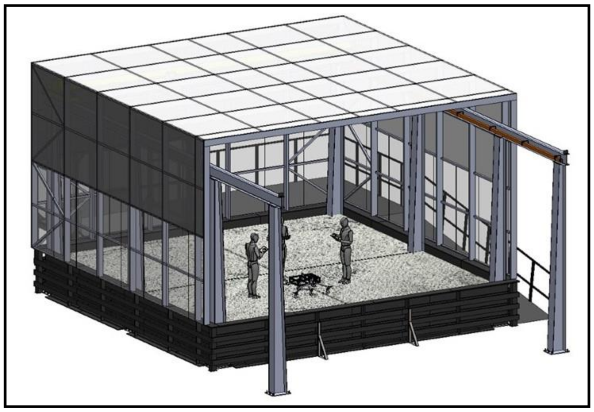

Figure 1. Perspective view of Exolith Lab's 100m^2 regolith bin design

Conclusions: A 100m^3 Lunar Highlands regolith bin opens the opportunity for researchers to test Lunar vehicles in similar conditions to the Lunar surface while on Earth. This regolith bin contains a high-fidelity simulant with a particle size and minerology simulating potential Artemis Lunar landing sites. High fidelity simulant coupled with other features such as gravity offload and variable terrain make it possible to recreate many of the aspects of the Lunar surface needed for hardware testing and ISRU studies.

More information about using Exolith Lab's 100m^2 regolith bin is available by request through exolithlab@ucf.edu.

References: [1] Exolith Lab, LHS-1 Spec Sheet (Dec. 2022). [2] Exolith Lab, LMS-1 Spec Sheet (Dec. 2022). [3] LHS-2: A Novel Lunar Highlands Regolith Simulant for Exolith Lab's Regolith Bin, P. Easter et al. LSIC Spring Meeting 2023

Space Kinetic's Lunar QB

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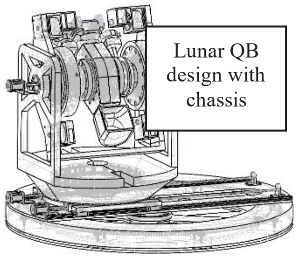
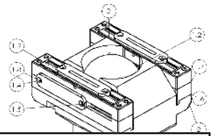
Introduction: DARPA's recently-announced LunA-10 program underscores the importance of a sophisticated, resilient lunar economy for long-term security and prosperity. One of the fundamental prerequsites for building a sustainable lunar economy is being able to efficiently transport resources, instruments, and other diverse payloads across the Moon's surface. However, this capability is currently made difficult by high lift costs and unforgiving terrain. Against this backdrop, Space Kinetic is developing the Lunar Quarterback (QB), an electromechanical 'throwing' technology that can launch diverse payloads across the lunar surface without requiring consumable propellant or significant infrastructure. The QB platform can also non-destructively catch inbound payloads launched from other QB systems.

Vision: Space Kinetic's Lunar QB will be the first platform that enables low SWaP-C long haul lunar surface logistics. The QB will act as the connective tissue that enables distributed mining operations, scientific outposts, and bases to tap into an integrated, on-demand supply chain. A QB-based logistics architecture will eliminate the most challenging issues faced by other lunar mobility solutions: the system will not be subjected to wear-and-tear from traversing regolith, will not have to contend with navigating variable terrain, and will have an expansive service area while maintaining a low mass profile (150kg QB will have a 25km service area, though the QB can be scaled).

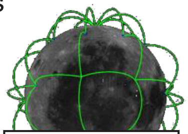
The Platform: The Lunar QB encompasses a motor system and electromechanical rotary arm that cradles a payload and spins up before releasing the payload towards its target, as well as a kinetic energy recovery system (KERS). The rotary arm includes both a release mechanism and a "catcher's mitt" to enable lanch-and-catch operations. The KERS recaptures and stores energy after the launch process through a regenerative braking maneuver. Each payload launched by the QB will be enclosed in a spherical capsule. To ensure accuracy, we designed a fixed launch angle release mechanism to eliminate launch angle variability.


Lunar QB design with chassis

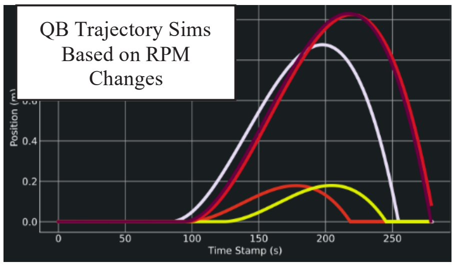

Release Mechanism

Features: Space Kinetic's Lunar QB platform is:

- *Modular*: The QB can be towed and repositioned by a rover, deployed off a lander, or integrated into mining, excavation, or power gen. sites.
- *Versatile*: The QB can support a broad mission set. By transporting batteries from different power generation sites, we can provide the power that enables operations throughout the south pole to survive the night; we can transport regolith from remote mining sites to a central refinery, and we can enable a distributed lunar base positioned far from lunar launchpads for dust mitigation purposes to be integrated into the supply chain.
- *Scalable*: The QB can scale at both the unit and architectural level. By making bigger QB systems, we can transport larger payloads across longer distances. By increasing the number of QB's in a given area, we can enable a multi-QB supply chain.
- *Nimble*: By varying the QB's launch angle, the QB can eliminate the challenges posed by variable terrain (e.g. we can launch over mountains and craters).
- *Sustainable:* The electromechanical QB has no associated plume or dust flareup at launch.


Scaled 'grid' network model

Development: Over the past 12 months, Space Kinetic has made swift progress on the development of the Lunar QB. We have secured a two-year CRADA with Los Alamos National Laboratory, executed a DoD SBIR award, and are collaborating with Aerospace Corp. on a paper focused on the QB. We have designed and are currently assembling our third prototype, enabling the QB system to reach TRL-5 by Q1 2024. We have also developed high-fidelity simulations showing how the QB system will operate across diverse use cases and ranges on the lunar surface. Space Kinetic will achieve TRL-6 in Q4 2024 and will be ready for its first in-space demonstration by Q4 2025.


QB Trajectory Sims Based on RPM Changes

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