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Tuesday April 16, 2024: Morning Session

<u>Session Title:</u> Low gravitational particulate structures, interactions and particulate mechanics
<u>Session Co-chairs:</u> S. Joseph Antony, Ph.D (University of Leeds, Leeds, UK) and Phil Metzger, Ph.D. (Florida Space Institute, University of Central Florida, Orlando, FL)
Room 124

10:20 AM **9976 - *Dilatancy phenomenon in fine soils - Microstructural considerations***

Mahdia Hattab - LEM3-CNRS/Université de Lorraine, Dan Zhao - Zhejiang University of Water Resources and Electric Power, Qian-Feng Gao - Changsha University of Science & Technology, Fares Bennai - LEM3-CNRS/Université de Lorraine, Pierre-Yves Hicher - GEM-CNRS/Ecole Centrale de Nantes

<u>Abstract:</u> Martian soils if overconsolidated may be exposed to a more or less significant dilatancy phenomenon due to any human or robotic activity on its surface. Dilatance is defined as negative deformation of the soil (increase in its volume) due to the evolution of the deviatoric stress in the soil.
This paper aims to characterize dilatancy phenomenon in fine soils (such as clays), especially how the microstructure properties evolve in relation with the strain mechanisms. The experimental approach consists in submitting the specimen to triaxial loading along purely deviatoric stress paths, in both normally consolidated and overconsolidated clay conditions. Then, the fabric state as well as the pore network properties are investigated using scanning electron microscopy. The results highlighted different particle orientation modes that could be activated at the local scale. These modes seem to be highly dependent on the stress level and the overconsolidation ratio. Microcracks were also found to develop across the sample accompanied by the occurrence of dilatancy.

<u>Keywords:</u> Kaolin clays
Triaxial tests
Microstructure
Multi-scale investigations
Scanning Electron Microscopy

10:40 AM **2105 - Modelling the continuous and staggered granular flows under reduced gravitational environments**

S. Joseph Antony - University of Leeds, Babatunde Arowosola - University of Leeds, Lutz Richter - OHB System AG, Tulegen Amanbayev - Southern-Kazakh State University

<u>Abstract:</u> Micromechanical behaviours of granular flows under reduced gravity levels are sought in space applications, for example, to understand and design efficiently the flow devices of the granular sample preparation and distribution systems of exploratory spacecraft. They are difficult to understand not only due to the discrete nature of the grains in granular assemblies but also due to the additional complexity of having to understand how the reduced gravity levels influence

inter-particle interactions and their eventual effects on the flow properties of grains through devices such as hoppers. Furthermore, understanding is lacking on to what extent the flow of granular materials through hoppers depends on whether the flow is enabled in a continuous or time-delayed staggered manner. To answer this, computer simulations are performed using the three-dimensional Discrete Element Method. The results clearly show the effects of particle-scale properties on the complex interactions between the grains and their subsequent effects on the micro-macroscopic flow relations of continuous and staggered granular flows of reduced gravitational environments compared with the earth's gravity.

Keywords: Space exploration
Granular mechanics
Micromechanics
Particulate Mechanics
Discrete Element Method
Particulate processing

11:00 AM **9683 - The development of the resonant pulse-elevator for granular materials**

Patrick Harkness - University of Glasgow, Xuan Li - University of Glasgow, Kevin Worrall - University of Glasgow, Andrew Scott-George - University of Glasgow, Bridgette Buss Crawford - University of Glasgow

Abstract: The pulse-elevator is a mechanism by which granular material can be uplifted in a narrow vertical channel. It has been proven to operate in microspheres, sand, and spoil, and delivers a highly-repeatable mass flow rate across a range of operating conditions [1]. This concept is entirely solid-state and can be used to uplift materials from hoppers or to replace an augering action in drillstrings. The key advantages are that the device does not need to be rotated, which means that it does not require a torque reaction; and the fact that it offers a high degree of design flexibility in confined spaces.
The mechanism is a series of alternating, opposing scoops which, when vibrated in any suitable waveform, allow material to move more easily in one direction than the other. The overall effect is similar to a Tesla valve, where each cycle of vibration completes with the material having moved forward one scoop, without any requirements for particle-surface friction or gross movement of the device itself.
Recent developments have shown that the device can also work in a horizontal direction, so that material can be moved in a complex path that follows the shape of a bespoke, solid-state device that is only vibrationally excited, as a solid body, in a single direction. This means that a pulse-elevator spoil handling system can be threaded through other systems, avoiding immovable obstructions along the way.
This paper will now focus on further improvements to the pulse-elevator and a performance comparison against a traditional auger arrangement. The pulse-elevator will be sprung so that the vibration action becomes resonant, which should reduce the power consumption and simplify the reacted vibrational forces into the support architecture, before being compared to a metre-class auger powered by an equivalent motor.
Given that the auger has been used in every planetary drilling mission to date, an alternative has significant disruptive potential. This paper will provide the first direct comparison, in terms of mass-flow-rate, energetic efficiency, and systems footprint, between a pulse-elevator and more traditional architectures.
[1] https://www.sciencedirect.com/science/article/pii/S0094576522003988

Keywords: Spoil handling
Granular transportation
Alternatives to augering

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Tuesday April 16, 2024: Morning Session

<u>Session Title:</u> Robotic Mobility, Navigation and Enabling Technologies
<u>Session Co-chairs:</u> Colin Creager (NASA Glenn Research Center, Cleveland, OH) and Robert Ambrose, Ph.D. (Texas A&M University, College Station, TX)
Room 114

10:20 AM **100 - *The Development and Characterization of the Shape Memory Alloy Spring Tire for Mars***

Colin Creager - NASA, Santo Padula - NASA, Vivake Asnani - Venturi Astrolab, Heather Oravec - NASA / University of Akron, John Breckenridge - NASA, Jim Benzing - The Smart Tire Company, Paria Naghipour - HX5

<u>Abstract:</u> The Shape Memory Alloy (SMA) Spring Tire is a non-pneumatic compliant tire developed by NASA Glenn Research Center, along with Goodyear Tire & Rubber Company to meet the needs of planetary rover missions on the Moon and Mars. This technology is a progression of the original Spring Tire, established circa 2010, which consists of coiled steel wires (springs) interlocked and formed into a toroid, allowing for high load carrying capacity and the ability to conform to the terrain. The implementation of SMA springs, which exhibit the 'psuedoelastic' phenomena and can withstand approximately 30 times more reversible strain than steel springs, expands the design space and capability of the Spring Tire technology. To specifically address the harsh terrain on Mars, which ultimately resulted in damage to the wheels on the Curiosity Rover in 2014, the SMA Spring Tire was adapted for Martian rover applications with a focus on durability. Extensive work was performed to mature the SMA Spring Tire to a Technology Readiness Level (TRL) of 6 for the Martian environment. This included developing new materials and spring manufacturing processes to meet the specific temperature needs on the Martian surface, advancing a custom user-defined phenomenological material model to predict the tire's response to load at temperatures, and improving the durability and performance aspects of the tires.
In 2019, the SMA Spring Tire was integrated into the baseline design for the Mars Sample Fetch Rover, which was to be a follow-up to the Perseverance Rover under the Mars Sample Return Campaign. Though a change in the campaign architecture in 2022 resulted in the cancellation of the Fetch Rover mission, extensive work was performed at GRC to produce and characterize a baseline flight Mars Spring Tire design. This paper will provide a high-level summary of the developmental work done to date on the Mars Spring Tire, and details on the current state of the art. An overview of the flight baseline design will be provided, as well as a discussion on tire modeling efforts. A summary of key test results, such as traction in soft soil, dynamic load response, and durability over a simulated Martian terrain, will also be presented. Lessons learned from the development and testing of the Mars Spring Tire will provide invaluable guidance for future planetary rover missions to the Moon, Mars, and beyond.

<u>Keywords:</u> tire
mars rover
mobility

traction
durability
mars sample return
spring tire
shape memory alloy

10:40 AM **1647 - ISRU Pilot Excavator Wheel Testing in Lunar Regolith Simulant**

Liz Zhang - NASA, Jason Schuler - NASA, Adam Dokos - NASA, Yinan Xu - NASA, Evan Bell - NASA, Thomas Muller - Bennett Aerospace

Abstract: The ISRU Pilot Excavator, or IPEx, is a robotic excavator funded by NASA's Space Technology Mission Directorate (STMD). The Concept of Operations for IPEx involves the robot driving on the lunar surface for over 150 miles at a speed of up to 30 cm/s. As such, it is critical to the mission's success to optimize the design of the wheels for performance in lunar conditions, specifically in lunar regolith. To achieve this, an array of tests was completed to observe the effects of various wheel design choices on the driving performance of the wheels in lunar regolith simulant.

In order to facilitate testing, we designed a 12" dia. configurable wheel to allow for interchangeability between various wheel formations. Two types of wheel parts were designed to be swapped: cleats, which form the tread of the wheel; and grousers, which protrude from the treads. The test variables that we considered were as follows: square vs. round wheel shape, solid vs. perforated cleats, cleat spacing, grouser height, and grouser spacing. By combining different settings of each of these test variables, ten discrete wheel designs were created and tested.

The configurable test wheels were mounted on the Regolith Advanced Surface Systems Operations Robot (RASSOR) developed at NASA's Kennedy Space Center. In our experiments, the robot was driven at a controlled speed across a prepared surface of BP-1 lunar regolith simulant. Four types of tests were conducted: circle driving, straight driving, slope driving, and drawbar pull. The driving tests were chosen to mimic a variety of conditions in which IPEx may be expected to operate, and the drawbar pull test was chosen to provide a standard of comparison with existing wheel design literature. The circle and straight driving tests were each performed at different levels: for the circle driving test, the robot was driven at a constant linear speed and three different angular speeds, while for the straight driving test, the robot was driven at three different linear speeds. The data collected from these tests included the power usage from each of the wheels, measurements of the tread patterns left in the regolith surface, and the amount of slip the wheels experienced, which was calculated using data from an OptiTrack motion capture system.

From the results of these experiments, we found that certain test variables were more significant than others in determining performance for each type of test, and no single wheel design clearly outperformed the others in all areas. The details of our findings will be discussed further in this paper. This data will be utilized to inform the design of the wheels for IPEx and can provide a basis for the design of wheels for future lunar terrain vehicles.

Keywords: ISRU
IPEx
RASSOR
Regolith
Drawbar pull
Wheels
Grousers
Driving

11:00 AM **1471 - A System for Exploring Craters and Shadowed Regions of the Lunar South Pole**

Robert Ambrose - Texas A&M, Micah Oevermann - Texas A&M, Meghali Dravid - Texas A&M

Abstract: In 2022 NASA identified candidate landing sites for near term missions to the Lunar south pole, which include steep slopes, low sun angles, and regions of local depressions where the sun does not shine. Deep craters near the geometric south pole are permanently dark, extremely cold (<100K) and orbital sensing suggest have trapped hydrogen, likely in the form of water ice. While the deepest of these features might yield the best astromaterial samples, they are too extreme for human exploration.

A robot with a soft, inflatable and spherical structure is proposed to roll down into such features to explore and collect samples, which can be scientifically evaluated in situ or ejected to the crater rim for human sample collection and return to Earth. The paper reports on the structural design of the spherical shell, the robotic control to guide it as it descends into the crater, and the payload bay which can carry a sample collection and ejection instrument.

The spherical shell design is ideal for the dust challenges of Lunar regolith, and provides an insulated volume to protect the system's battery and electronics from a crater's thermal extremes. The spherical shape has a minimum of features and penetrations, minimizing environmental complexity thru a simple geometry. Applications of space suit materials such as Teflon, Kevlar and Nomex will be described to make the shell durable, using a combination of a pressure bladder and external restraint layer like a space suit.

The control uses an Inertial Measurement Unit to manage the rolling speed and steering of the ball as it descends, with cameras and other sensors recording and transmitting the descent path to the crew's rover or communication repeater on the crater's rim. The central payload bay can carry instruments for periodic deployment during the descent, a single large payload, or a mix utilizing its 16U total capacity. Experimental results will show the system's ability to roll in a straight line, or steer to avoid obstacles like a rover but with a simple spherical shape.

Filled with an inert gas such as argon (Ar), the inflated pressure of <30KPA ensures the gas does not condense, and bathes the electronics in a convective fluid. This gas both cools the electronics and uses that heat to avoid condensing and the pneumatic control adapts the pressure as the temperature changes. Experimental results will be presented on the control of the sphere's pressure and the impact on the bouncing and damping of the motion as it rolls. The sphere's pressure can be adjusted based on observed dynamics, reducing or increasing pressure to help adapt to soil and terrain conditions.

The paper will conclude with experimental results showing multiple sizes of the spherical system, from 60cm to 180cm diameters. Steering control of the sphere at speeds exceeding 5 m/s will be shown, as well as performance is soft and hard packed soils. Able to drive on water, the design will also be shown for terrestrial (littoral) applications.

Keywords: Lunar
Exploration
Crater
Shadow
Robot

11:20 AM **2991 - Real-Time Visual-Inertial Odometry for Planetary Exploration: Preliminary Tests**

Junho Gong - Korea Institute of Civil Engineering and Building Technology, Jong-Ho Na - Korea Institute of Civil Engineering and Building Technology, Sungchul Hong - Inha University, Tae-Hoon Kim - Korea Institute of Civil Engineering and Building Technology, Hyu-Soung Shin - Korea Institute of Civil Engineering and Building Technology

Abstract: In the new space age, both numerous countries and companies with space programs have been participating in research areas of space exploration and spaceport construction as well. In South Korea, the Korea Pathfinder Lunar Orbiter, officially Danuri, was successfully launched in 2022 and has been taking missions of surveying lunar resources. Because of the orbiter, the Korean Aerospace Research Institute has announced that a lunar orbiter, a lunar lander, and a rover will be launched together on a Korea Space Launch Vehicle-3 by 2032. In the third phase of the Artemis program, a moon landing will be planned to spend a week exploring the surface in 2025. For such long-term missions in the lunar surface environment, In-Situ Resource Utilisation (ISRU) constructions will be essential for various purposes such as shelters, spaceports, blast barriers and so forth. In order to construct infrastructure, Geospatial information is crucial to be prepared. The lunar exploration rovers have been developed to take not only obtaining this information but also surveying resources. However, due to the extreme environmental conditions and technical constraints of the moon, there are numerous limited circumstances to estimate the actual location of the rovers and establish the geospatial information. To solve this problem, we developed a rover that applied Visual Inertial Odometry (VIO) and deep learning-based simultaneous localization and mapping (SLAM) algorithm. Accordingly, we would like to introduce the results of evaluating 3D mapping performances in the simulated planet test beds.

Keywords: Visual-Inertial Odometry
Rover
Planetory exploration
ISRU
Spaceport construction

11:40 AM **1369 - Reverse-Ephemeris Lunar Navigation for NASA and Commercial Exploration**

Robert Moses - Director, Innovation & Technology, Michael McBeth - Department of the Navy (at NASA Langley Research Center)

Abstract: Lunar navigation systems are needed for future Moon missions to enable rover navigation, mining, construction, human exploration, and autonomous operations. Lunar construction requires centimeter-scale position accuracy not typically found in navigation solutions previously used for lunar and Mars exploration. The need for high accuracy and low cost provides competing demands for solution developers.

Orbit determination of satellites and resident space objects often involves observations from a benchmarked surface position to establish the orbiting body's ephemeris. In our concept, we reverse this process to make range and range-rate measurements of an orbiting body with a known ephemeris. Using these measurements and an accurate clock we obtain a position fix on the surface. The range measurement results in a conic section that produces a circle on the surface of the Moon's ellipsoid while the range-rate measurement produces a parabola that intersects the circle at two points. One of the points can be eliminated as the position by a priori knowledge, repeated measurements over time, or measurements from a second satellite. With our approach a position fix can be obtained with one set of measurements from one orbiting body. Obtaining a position fix from a Global Navigation Satellite System like GPS requires measurements from three to five orbiting satellites depending on the accuracy required.

In FY20, we developed a point design to study the feasibility of the approach. We allocate the system complexity between the lunar surface segment and the lunar orbital segment to realize a translating transponder solution. Our point design consists of a lunar surface S-Band (2,400 – 2,450 MHz) 10-Watt transceiver and a three-satellite constellation in a frozen elliptical orbit to provide two-fold continuous coverage of the Moon's southern hemisphere. For our point design we evaluated an analog translating transponder that could serve up to 300 users by allocating each a 3 kHz bandwidth channel plus an unused guard channel which works out to 600 3 kHz channel segments or 1.8 MHz of bandwidth at the transponder. While our point design is based on an analog approach, we envision a fielded version based on digital technology.

Here we show that there is sufficient margin to close the link between a 10-Watt lunar surface transceiver with an S-Band helix antenna with 10 dB of gain and a satellite at apolune with a transponder payload assumed to have a noise temperature of 500K, bandwidth of 1.8 MHz, and a gain of 110 dB. The satellite transmit and receive antennas are assumed to have a gain of 26 dB.
The purpose of this paper (or poster) is to illustrate the functional operations of this reverse-ephemeris system to provide lunar navigational support for exploration, construction, mining, and other lunar surface activities and to highlight plans at Tamer Space to implement this Reverse-Ephemeris Lunar Navigation concept to support the Artemis Program and commercial operations on the lunar surface.
Reference: https://technology.nasa.gov/patent/LAR-TOPS-361

Keywords: Lunar Surface Navigation System for Robotics Automation and Control
Navigation support for exploration construction mining and other lunar surface activities
reverse-ephemeris lunar navigation system

FINAL (Updated: 04/12/24)

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Tuesday April 16, 2024: Morning Session

Session Title: Design and Construction of Structures in Extreme Terrestrial and Extraterrestrial Environments

Session Co-chairs: Sudarshan Krishnan, Ph.D. (University of Illinois at Urbana-Champaign, IL) and Nilanjan Mitra, Ph.D. (Johns Hopkins University, Baltimore, MD)

Room 126

10:20 AM **5715 - *Decentralized Earth Housing system derived from Space habitats design***

Samer El Sayary - Assistant professor of architecture

Abstract: With the accelerating pace of potential existential risks and possible mass extinction events, new strategies have to be adopted in the design of human habitation systems on Earth. Dealing with Earth as an already deserted planet and starting from there, architects, urban planners, and even interior designers have to shift their design mindsets towards lessons learned from designing outer space and planetary surface outposts. The presented work is a set of internationally awarded architectural projects based upon a scientifically published theoretical framework developed during the last 15 years, associating field studies and desk studies with an experimentally judged architectural practice. The presented Earth housing projects propose a new blueprint for architects and designers to rethink the traditional sustainability definitions, suggesting acts and actions for creating a decentralized, off-grid, self-sufficient, self-regulating, zero-energy, zero-waste capacity to exceed the role of the traditional housing system as a reconciler and contributor to the enrichment of the environment instead of only saving its resources for future generations in alignment with the United Nations goals numbers 1,2,3,6,7,8,11,13 2, 3, 6, 7, 8, 11, 13, and 15.

Keywords: Decentralized housing system
Earth habitation system
life support systems
space architecture

10:40 AM **4814 - Structural Analysis of Sandbag Topology for Lunar Infrastructure Applications**

Yinan Xu - University of Arizona - SpaceTREx, Siva Muniyasamy - University of Arizona - SpaceTREx, Carlos Doe - University of Arizona - SpaceTREx, Jekan Thangavelautham - University of Arizona - SpaceTREx

Abstract: The next milestone of space exploration is to develop support structures on the Moon's surface to expand exploration to the four corners of the Moon and beyond. To move into this next phase of lunar exploration and development, solutions need to be developed for a lunar infrastructure. With a limited supply of resources on the Moon, utilizing most of what's available will prove to be essential. Thus, the use of smart sandbags filled with lunar regolith will prove to be critical in constructing lunar infrastructure.

Before constructing infrastructure with the sandbags, analysis must be performed to ensure structural integrity. Analysis focuses on constant and impact forces on the sandbag design to discover areas of stress failures and deformation failures. These analyses imitate the behaviors of micrometeor impacts that affect the integrity of the structures. Likewise, the sandbags must be able to withstand the load of several other regolith sandbags on top of each other. Management of load, force, and impact is crucial to the performance of the sandbag. This is to ensure that astronaut homes, research facilities, storage containers, landing pads, launch sites, and other critical components to the future lunar base are thoroughly protected from the lunar environment.

The sandbag design contains three key areas of stress and deformation. The two greatest areas of stress lie on the side where force is applied on the opposite face of where the force is applied when applied from a vertical direction. When applied from a horizonal direction, only the applied side is affected. The location where deformation occurs the most is where the force is applied. These initial findings help pinpoint how best to support the sandbag for structurally loading and to improve its ability to mitigate impact.

The next phase of analysis focuses on the structural integrity of infrastructures made of multiple sandbags. This next focus will also analyze different sandbag topologies and infrastructure designs that will improve the structural integrity of the lunar habitat. Work will determine what aspects of lunar construction will prove to be critical for development. Future work will also analyze the thermal integrity of the sandbags due to the heat of micrometeorites and the solar radiation experienced by the sun.

Keywords: sandbag
Moon
surface infrastructure
excavation
construction

11:00 AM **5761 - Material response at extreme lunar environments**

Nilanjan Mitra - Johns Hopkins University

Abstract: A combination of extreme environments on the moon presents challenges to human settlement. The extreme lunar environment includes:

- Sharp temperature gradients (diurnal variations more than 300 K).
- The presence of both significantly high and low temperatures (exhibiting a range from -40 to 400 K).
- A radiation environment (consisting of ionizing radiations such as galactic cosmic radiation, solar energetic particles, as well as non-ionizing radiations such as UV).
- Micrometeorite impact (impact velocities greater than 2 km/s), moonquakes.
- Energetically charged dust accumulation.
- Vacuum atmosphere and low gravity.

Materials exposed to these extreme conditions undergo changes in their molecular structure, resulting in changes in properties. These property changes affect the behavior of the resultant structure. In fact, changes in the molecular structure of material also affect its chemical performance (required as in the hydration of cement with other constituents to yield concrete). The presence of a vacuum atmosphere along with low gravity can result in problems associated with processing and construction, which are not easily realizable on Earth (such as the flow of concrete slurry).

This talk focuses on materials subjected to two extreme conditions: radiation environment and hypervelocity micrometeorite impact. Gamma radiation (Co-60) on lunar simulants (JSC-1A and OPRH2N) revealed changes in color to the sample, indicating the formation of radical groups upon bond dissociation. These radical groups will affect the chemical performance of the materials.

Another extreme condition to be presented in this talk will involve micrometeorite impact. The global response of hypervelocity impact demonstrates the formation of crater and ejecta cloud, which varies depending upon the initial material properties. In addition, shock waves travel within the material, changing the properties of the inherent material, which might lead to phase transformations. Case studies of different materials under these two conditions will be presented in the talk to highlight the importance of understanding changes in materials, which can have catastrophic effects on the performance of the structure composed of the material.

Keywords: Micrometeorite impact
Ionizing radiation
Materials
Extreme condition
Lunar atmosphere
Phase transition
Free Radical

11:20 AM **8138 - Hot deformation of metallic honeycombs: Mechanisms and modelling**

Yuanbo Tang - University of Oxford, Yulan Zhang - University of Texas Austin, Enrique Alabort - Alloyed ltd, Roger Reed - University of Oxford

Abstract: Metallic lattice structures, sometimes known as mechanical architected materials, are attractive for various reasons. First, it has a low relative density compared to its monolithic counterparts, thus being relevant for lightweight applications for transportation. Second, such structures absorb significant energy before fracture, which allows for commendable dampening and shock resistance properties. Third, it is possible to allow for additional functionalities with appropriate cellular design, such as the enhancement of bone ingrowth in biomedical implants. Despite a range of metallic structures that were proposed and experimentally validated, limited, if any study reported their high-temperature properties. This is the original motivation for achieving the design freedom of complex geometries for AM superalloys, which is a recent possibility with the recent alloy design success. Transformative engineering innovations will be leveraged if this is proven successful. For instance, higher specific strength and creep-resistant turbine components can be developed, hence significant weight reduction and fossil fuel savings are forecasted. Furthermore, the ability to manufacture intricate and more effective cooling channels is expected via AM, which will increase the operation temperature that increases thermal efficiency. AM-enabled superalloy lattices are expected to play a significant role in setting transformation for future sustainable aviation and space exploration.
This work concerns the processing, characterisation and modelling of the deformation behaviour of cellular metallic structures at both room temperature and 900 degC ranging about one decade of relative density. We aim to develop a comprehensive understanding of the deformation mechanisms and their interplay with damaging routes for a range of temperatures. In this work, we focus on the established honeycomb structures, rather than more complex shapes for the avoidance of uncertainty arising from local geometric factors. ABD-900AM was chosen as the material due to its superior printability and high-temperature performance. Different deformation mode, such as plastic hinge, ductile and brittle collapse, was studied as a function of temperature and t/l ratio (strut thickness/length). The influence of oxidation and the material's intrinsic ductility was discussed. Consequently, a model based upon finite element analysis (FEA) was constructed by incorporating appropriate damaging criteria which gives accurate behavioural predictions. This work has validated the possibility and identified mechanical constraints for the future development of high temperature metamaterials.

Keywords: high temperature deformation
honeycomb

additive manufacturing
superalloys

11:40 AM **178 - A Mesoscale Framework to Model the Deformation Behavior in Metals under Hypervelocity Impact**

Ching Chen - Department of Materials Science and Engineering, Institute of Materials Science, University of Connecticut, Avinash M. Dongare - Department of Materials Science and Engineering, Institute of Materials Science, University of Connecticut

Abstract: One of the critical challenges in the design of future Lunar infrastructure and operations is the survivability of materials under impact by micrometeoroids at velocities of up to tens of km/s. These extremes in impact velocities can result in catastrophic failure, partial penetration, or local deformation that affects the survivability and performance of lunar structures. The ability to design these structures, therefore, requires a fundamental understanding of the mechanisms of deformation and failure of materials under such extreme loading conditions. The current understanding, however, is largely limited by experimental capabilities that are unable to characterize the localized mechanisms of plastic deformation and the shock wave propagation behavior that can initiate dynamic failure. As a result, computational methods have been used to predict the response of materials under hypervelocity impact. Several continuum methods are used typically to predict the response of materials at the length scales of the projectiles (a few microns to a few mm) at velocities of up to 10 km/s. However, the predicted response in these simulations is determined by the accuracy of the materials models for high-rate deformation and dynamic failure. The main challenge in the reliable prediction of the dynamic response, therefore, relies on extracting critical information for these phenomena where resolutions provided by experimental techniques are either incapable due to theoretical limits or are far too expensive or inefficient.
This talk will present a bottom-up approach to address this challenge. A computationally efficient mesoscale model called Quasi-Coarse-Grained Dynamics (QCGD) is developed to predict the localized mechanisms of plastic deformation under impact at the length and time scales of micrometeoroid impacts. The QCGD method is based on the coarse-graining of material microstructures using representative atom (R-atom) and solving the equations of motion for the R-atoms using scaled interatomic potentials to retain the energetics of materials and the deformation behavior (equation of state and high rate response). The QCGD simulations are carried out to predict the dynamic evolution of localized temperatures, pressures, and the related shock wave propagation behavior during the impact of 20 µm Al powders onto Al substrates at velocities ranging from 2 km/s to 10 km/s. In addition, the QCGD framework is combined with a two-temperature model (TTM) to model laser energy deposition in metals and understand the role of laser parameters and material properties on the acceleration of particles with dimensions of a few microns to tens of microns. The QCGD-TTM framework serves as a tool to investigate the capabilities of lasers to achieve particle impacts at velocities greater than 10 km/s The talk will discuss the mesoscale framework and the links between laser energy, materials properties, and flyer/particle velocities for thicknesses/sizes of up to 100 microns.

Keywords: Micrometeoroids
Hypervelocity Impact
Metals
Quasi-Coarse-Grained Dynamics (QCGD)

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Tuesday April 16, 2024: Morning Session

<u>Session Title:</u> Specialized Sensors-based Structural Damage Detection and Health Monitoring
<u>Session Co-chairs:</u> Gangbing Song, Ph.D. (University of Houston, Houston, TX) and T. Tafsirojjaman, Ph.D. (The University of Adelaide, Adelaide, Australia)
Room 128

10:20 AM **8521 - *Detection of Crack Propagation of Reinforced Three-Point Bending Beams Using Smart Aggregate Transducers Enabled Time Reversal Method***

Lingzhu Zhou - Dongguan University of Technology, Yu Zheng - Dongguan University of Technology, Gangbing Song - University of Houston, Lifei Zhang - Dongguan University of Technology

<u>Abstract:</u> The fracture process of reinforced concrete structures plays a vital role in the assessment of structural safety. It is difficult to evaluate crack propagation status and quantify the damage level of reinforced three-point bending beams with traditional monitoring techniques, such as linear variable differential transformer (LVDT) sensors and electrical resistance strain gauges. Therefore, it is essential to detect the crack propagation in reinforced three-point bending beams using some novel monitoring technologies. In this paper, a total of ten pre-cracked reinforced beams, which varied in the type of reinforcing material, initial crack-depth ratio, thickness of concrete cover, diameter of reinforcing bar and type of concrete material, were fabricated and subjected to three-point bending test. The smart aggregate (SA) transducers using lead zirconate titanate (PZT) were utilized to detect the crack propagation and the fracture process of those reinforced three-point bending beams. A pair of SA transducers, serving as an actuator and a sensor, were placed on both sides of a pre-fabricated crack in the reinforced three-point bending beam. The time reversal technique was adopted to obtain a clear focused signal amplitude and reduce the noise-to-signal ratio. The experimental test results reveal that the amplitudes of the received signals and focused signals are decreased by increasing the applied load from the micro-crack initiation to the instability failure stage of the reinforced three-point bending beams. This is attributed to the development of pre-fabricated crack in reinforced three-point bending beams which hinders the propagation of stress waves. In addition, the amplitude ratio is defined by using the focused signals to identify the crack propagation status and the damage index is proposed to quantify the damage level. The four-stage fracture failure process of reinforced three-point bending beams, namely the linear elastic stage, the micro-crack propagation stage, the macro-crack propagation stage and the instability failure stage, can be detected using the amplitude ratio. The damage level of reinforced three-point bending beams in various damage stages can be quantified using the damage index.

<u>Keywords:</u> Crack Propagation
Damage Status
Reinforced Three-Point Bending Beams
Smart Aggregate (SA)
Time Reversal Method

10:40 AM **9129 - Quantifying the Impact of Sensor Degradation on Data-Driven Fault Detection Strategies in Resilient Space Habitats**

Zixin Wang - Purdue University, Manuel Salmerón - Purdue University, Herta Montoya - Purdue University, Mohammad Jahanshahi - Purdue University, Shirley Dyke - Purdue University

Abstract: Structural health monitoring (SHM) is a key element in designing resilient spatial habitats. Using SHM, the health management system can assess the habitat condition, make decisions, and take necessary actions based on the detection results. The sensors used for data acquisition are the first step in the data flow pipeline. Hence, their ability to gather reliable data is of paramount importance for the success of the SHM strategy.

Accelerometers are commonly employed sensors for acquiring dynamic response data from structures. However, like any physical device, sensors degrade over time due to various factors such as environmental conditions, mechanical wear, and aging. As a result, the acquired data may become less reliable and accurate, potentially impacting the performance of fault detection algorithms.

This research focuses on quantifying the influence of sensor degradation on the performance of a data-driven fault detection system. The proposed study utilizes an ASCE benchmark model that simulates different health conditions of a four-story steel frame structure, where the accelerometers are subjected to accelerated degradation profiles based on realistic degradation models. A comprehensive analysis is conducted to evaluate the deterioration in sensor performance and its subsequent effect on the accuracy of the fault detection algorithm. By systematically varying the degree of sensor degradation, the study aims to identify critical thresholds beyond which the performance of the fault detection algorithm becomes compromised. An unsupervised fault detection approach is developed based on active sensing, autoencoders (AEs), and information fusion. The dynamic response data are acquired by several accelerometers deployed on the structure, which can be excited at different locations using robotic excitation mechanisms. The fault detection is performed by the AE which is trained in an unsupervised manner. The continuous wavelet transforms under the healthy state of the structure are utilized to train AEs. To enhance the robustness of the approach to real-world uncertainties and sensor degradation, several information fusion strategies are proposed. The proposed fault detection approach enables the identification of potential damage, irregularities, or anomalies that may compromise the habitat's structural integrity and functionality.

The outcomes of this research will contribute to developing improved strategies for managing and mitigating the impact of sensor degradation on the performance of data-driven fault detection systems in space habitats. Ultimately, this will enhance the accuracy and robustness of SHM algorithms, enabling proactive maintenance and ensuring the continued safety and functionality of space habitats in challenging environments.

Keywords: Structural health monitoring
Fault detection and diagnosis
Unsupervised learning
Sensor degradation
Resilient space habitats

11:00 AM **5900 - Damage Identification of Concrete Structures Using Hybrid Method Based on Piezoelectric Signal**

Lei Wang - School of Civil Engineering, Changsha University of Science and Technology, China, Lingzhi Ou - School of Civil Engineering, Changsha University of Science and Technology, China, Lizhao Dai - School of Civil Engineering, Changsha University of Science and Technology, China

Abstract: The piezoceramic sensor is widely used for damage identification of concrete structures due to high sensitivity and real-time monitoring. However, the identification results of piezoelectric sensor exhibit significant discreteness. An effective hybrid method is proposed in the present study to identify the damage of concrete structures. The hybrid method consists of three modules: piezoelectric signal acquisition, feature extraction combining wavelet packet transform and singular value decomposition (WPT-SVD) and pattern recognition of improved back propagation neural network (BPNN) models.

Piezoelectric signal is selected to detect the damage of concrete structures because it has varying degrees of attenuation through different size of cracks. The attenuation of piezoelectric signal can be reflected in the energy change of its time domain and frequency domain. The signal can be converting into non-overlapping narrow frequency bands with equal bandwidth by WPT. Based on this, the time-frequency domain matrix with damage information is constructed. Due to the high dimension of the time-frequency domain matrix, it is transformed into a low-dimensional matrix consisting of singular value vectors with damaged features using the algebraic and geometric invariance of SVD. The BPNN is established to map the nonlinear relationship between singular value vectors and damage states. It can address the discreteness of identification results of piezoelectric signals. The genetic algorithm (GA) and the improved whale algorithm based on chaotic mapping and adaptive weight (CIWOA) are used to improve the identification accuracy of BPNN by giving optimal weights and thresholds.

A static loading experiment was carried out to record the piezoelectric signals from the healthy state to failure state of prestressed concrete (PC) beams. Three specimens were loaded to failure in the experiment, and the lead zirconate titanate (PZT) patches on the surface were used to transmit scanning signals. The experiment results reveal that the development of cracks is the main reason for the damage of PC beams in the experiment, which can be used as typical features to reflect the damage evolution. The singular value of the time-frequency matrix decreases gradually with increasing load after feature extraction. The normalized singular value vector distance exhibits a three-stage correspondence with the damage condition of uncracked stage, crack development stage and failure stage. It indicates that the singular value vector is an effective feature parameter for the damage of concrete structures. The identification results of GA-BPNN and CIWOA-BPNN are more stable and accurate as compared with BPNN. The identification accuracy for structural damage location and degree are 99.6% and 94.5% using GA-BPNN, which are 99.4% and 93.8% using CIWOA-BPNN. This indicates that the proposed hybrid method can efficiently identify the damage of concrete structures.

Keywords: concrete structures
damage identification
piezoelectric signal
singular value decomposition
BPNN

11:20 AM **2967 - An Edge-Computing-based structural health monitoring system and applications**

Peng Zhang - Dalian Maritime University, Ran An - Dalian Maritime University, Zhengjie He - Dalian Maritime University, Liang Ren - Dalian University of Technology

Abstract: Structural health monitoring (SHM) techniques have been extensively studied and widely applied to obtain the performance of infrastructures in order to prevent structural failure. In a traditional SHM system, however, the structure response obtained by the data acquisition (DAQ) device has to be transmitted to a centralized computer or Server for further interpretation, imposing a high requirement of communication bandwidth.

This paper aims to relocate part of the data processing tasks from the centralized computer/Server to an edge computing device. This edge-computing-based SHM system can be divided into three

layers: hardware, data processing, and applications. The hardware layer consists of a Raspberry Pi, an open-source DAQ, and sensors. The structural response obtained by the sensors will be transferred to a digital signal using the DAQ and transmitted to the Raspberry Pi. The Raspberry Pi is the core of the edge-computing-based SHM system. All functions or algorithms are deployed and executed in the Raspberry Pi. The data processing layer aims to extract high-value information from the observed structure response. In this study, for instance, a novel operational modal analysis (OMA) algorithm is coded in Python. Using this algorithm, a huge amount of acceleration signal (often of several M bytes) will be replaced by several numbers of modal information. Derived data will be stored and displayed using a web application in the application layer. This web application is developed using JavaScript and Python. JavaScript and libraries such as Apache Echarts are used to develop the frontend of the web application. While, the backend is developed by Python and the Flask Library. Interaction between the front and back ends was enabled by the WebSocket protocol.

Several experiments have been performed to test the feasibility and reliability of the proposed edge-computing-based SHM system. The first test aims to examine the accuracy of the Raspberry Pi-based SHM system. Five pairs of strain gauges are installed at five nodes of a flexible structure. The gauges are connected to a Raspberry Pi and a centralized computer, respectively. The strain measured by the Raspberry Pi-based system and the centralized computer-based system is quite close, implying the satisfying accuracy of the edge-computing system. The second test aims to examine the OMA function. Four acceleration sensors are installed on the structure to obtain the first-order frequency. The frequency obtained by the OMA algorithm and an impact test agreed well implying the satisfying accuracy of the algorithm.

Compared with the traditional centralized SHM system, the edge-computing-based SHM system have no requirement for data transmission and thus is more suitable for SHM of structures located in remote or extreme environments.

Keywords: structural health monitoring
operational modal analysis
edge computing
SSI

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Tuesday April 16, 2024: Morning Session

<u>Session Title:</u> Design and Analysis of Habitat Structures and Facilities on the Moon and Mars
<u>Session Co-chairs:</u> Ramesh B. Malla, Ph.D., F. ASCE (University of Connecticut, Storrs, CT) and Juan H. Agui, Ph.D. (NASA Glenn Research Center, Cleveland, OH)
Room 117

10:20 AM **902 - *Design, Analysis, and Implementation of Modular Blocks for Lunar Habitable Infrastructure***

Nerma Caluk - Florida International University, Atorod Azizinamini - Florida International Univeristy

<u>Abstract:</u> It has been more than five decades since the most recent human exploration resulted in new footprints on the lunar surface. The ongoing Artemis mission envisions establishing a sustained human presence on the Moon and conducting research through collaborative efforts with international and commercial partners. Thus, a need for a safe and resilient habitation system, capable of accommodating both short-term and long-term human missions is of great importance. Following the publication of a trade study on various habitation system concepts at the ASCE Earth & Space conference by the same authors, a modular block lunar construction approach was identified as the most optimal strategy for preliminary design and analysis. To appropriately design and optimize the constituent components of the habitation system, it was imperative to address several aspects of the structure on a global scale. This paper encompasses extensive research conducted as part of the first author's dissertation work, which commenced by exploring the interconnected characteristics of the overall shape and net habitable requirements for the residing crew members. Subsequently, the paper addresses different constructability approaches, ultimately selecting the implementation of small lunar regolith rovers capable of uphill transportation and placement of the modular blocks, along with the infusion of lunar soil into their cavities. A thorough trade study of construction materials and manufacturing processes was conducted, resulting in the selection of polymer-based concrete through additive manufacturing methodologies. With the foundation parameters and assumptions established, the paper progresses to detailed design and optimization of individual blocks, followed by consideration for roof design, associated connection, and foundation design. The final chapter presents the structural analysis, considering the lunar environmental and loading conditions, with the main focus being superimposed internal pressure of 69 kPa and lunar gravitational acceleration, and the seismic assessment of the analyzed lunar habitation system.

<u>Keywords:</u> NASA
Artemis
Lunar Habitat
Lunar Infrastructure
Finite Element Analysis
Civil Engineering
Structural Engineering

Modular Blocks
Habitation

10:40 AM **1307 - Engineering Design of Lunar Structure Regolith Shielding to Resist Hypervelocity Meteoroid Impacts**

Sushrut Vaidya - University of Connecticut, Ramesh Malla - University of Connecticut

Abstract: A properly designed regolith cover may protect lunar structures from hazards such as extreme temperature variations, dangerous radiation, and meteoroid impacts. This paper presents a systematic analytical method for meteoroid impact-resistant design of regolith shielding, based on the physics of shock waves generated during hypervelocity impacts. The initial shock pressure and energy partition between impactor and target (i.e., regolith shield) are calculated using the planar impact approximation for hypervelocity collisions. Shock wave expansion and shock pressure attenuation within the regolith shield are modeled assuming that the energy transferred from impactor to target is uniformly distributed throughout a hemispherical volume of regolith, neglecting irreversible energy loss due to heating of the regolith as the shock wave expands into the regolith shield. Owing to its similarity to lunar soil, dry sand is used as a model to idealize the behavior of regolith under hypervelocity impact. Linear shock velocity-particle velocity equations of state are used to model material behavior under shock loading. Practical application of the shock physics-based design method is illustrated by performing a parametric analysis to calculate the regolith shielding thickness required to prevent yielding of the underlying aluminum structure in typical impact scenarios. The regolith thickness required for ensuring that the shock pressure decays to the yield strength of the underlying structural layer is compared with that required for preventing impacts that completely penetrate the regolith shield, which is calculated using an empirical equation. The results indicate that, in a majority of cases, the regolith thickness required for preventing penetrating impacts is likely to ensure attenuation of impact pressure sufficiently to protect the underlying structure. From an engineering design standpoint, the analytical method presented in this paper provides an important tool for designing impact-resistant regolith shielding for lunar structures.

Keywords: Lunar structures
Micrometeoroid impacts
Hypervelocity impacts
Shock wave theory
Planar impact approximation
Shock pressure attenuation
Regolith shielding
Engineering design

11:00 AM **9754 - Seismic Vulnerability Assessment of Non-Structural Elements Inside an Inflatable Lunar Habitat**

Oscar Forero - Purdue University, Julio A. Ramirez - Purdue University, Shirley J. Dyke - Purdue University

Abstract: The spirit of exploration and pursuit of knowledge are once again driving humanity to seek a human presence on extraterrestrial bodies. While numerous challenges must be overcome to achieve this goal, the existence of moonquakes has often been overlooked. The Apollo Passive Seismic Experiment (APSE) collected eight years' worth of data, offering the scientific community insights into the Moon's internal mechanisms. Using NASA's Moon to Mars Architecture requirements for surface habitation, a procedure for vulnerability assessment is developed herein for essential non-structural elements (NSE) inside an inflatable habitat. The NSE element used for this study is the environmental control and life support system (ECLSS).

The aim of this study is to propose an approach to assess the vulnerability of the NSE that supports essential equipment under a paucity of information related to the seismic hazard. We also emphasize herein that the launch dynamic environment behaves differently, yielding a need to equip a future habitat with seismic mitigation measures. The findings in this work suggest that due to epistemic uncertainty, significant disturbances may result in long-lasting vibrations that need to be considered as they may require effective mitigation measures.

Keywords: Moonquakes
Non-structural elements
Seismic Vulnerability
Lunar Habitat
Launch environment

11:20 AM **6415 - Dynamic Response Analysis of Lunar Structures with Regolith Covers**

Hamed Seifamiri - Polytechnique Montreal, Pooneh Maghoul - Polytechnique Montreal, Roberto de Moraes - AECOM, Ramesh B. Malla - University of Connecticut

Abstract: The establishment of safe and resilient habitats on Mars and the Moon requires meticulous attention to the design and construction of structures capable of shielding astronauts and materials from the inhospitable environments. Various factors, including seismic sources such as meteorite impacts, underground magma pressure, and rapid temperature fluctuations, must be carefully considered. Numerous conceptual designs for lunar and Martian structures, such as deployable, 3D-printed, and generic surface geostructures, have been proposed in existing literature. Recently, there has been increasing interest in utilizing lunar or Martian lava tubes as potential shelter options.

In this study, we focus on investigating the dynamic behavior of semi-circular Lunar structures with different types of regolith covers, such as regolith blankets or buried substructures. Through simulations of six Lunar structure models under two seismic sources - artificial impact signals and vertically propagating SV shear waves - we aim to assess the fundamental characteristics of the dynamic response exhibited by various regolith cover systems. Our simulations employ SiteQuake, an in-house numerical software utilizing Finite Element (FE)/Boundary Element (BE) computational method. FE modeling is employed for the Lunar structures and their regolith-shielding systems, while BE modeling is used for the bedrock and absorbing boundaries to mitigate wave reflections.

To simulate the meteorite impact signal, we employ a source function dependent on the physical and mechanical properties of the impactor and the impacted surface. For the earthquake simulation, we consider in-plane SV-P seismic waves propagating through the medium. Our investigation primarily focuses on analyzing the Spectral Amplification (SA) and Dynamic Stress Concentration Factors (DSCF) to evaluate the seismic response. SA is determined by comparing pseudo-acceleration values of simulated spatial points to a reference spectrum, while DSCF provides insights into stress concentration.

The results reveal the intricate and complex dynamic interactions between structures and regolith shielding, highlighting the entrapment of seismic waves in the soft regolith shield and lower energy absorption by the main structure. The study also demonstrates distinct amplification patterns influenced by the topography of the structure's site (curved or flat) and the properties of the regolith cover (such as stiffness and geometry) employed. Unshielded structures situated in concave topographies, such as craters or pits, are identified as the most vulnerable, while lava tubes exhibit the lowest dynamic amplification values, making them comparatively safer options. The behavior of other structures falls between these extremes, based on their respective shielding systems.

This research provides valuable insights into the design and dynamic analysis of Lunar structures with regolith covers, offering implications for astronaut protection and habitat design in extreme environments. The findings contribute to our understanding of the complex interplay between structures, regolith shielding, and seismic forces, enabling the development of robust and resilient habitats for future space exploration missions.

Keywords: Lunar structures
Regolith covers
Seismic response
Structure protection
Habitat design

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Tuesday April 16, 2024: Afternoon Session

<u>Session Title:</u> **The Physics of Regolith I: Mechanics, Heat, and Volatiles**
<u>Session Co-chairs:</u> Mahdia Hattab, Ph.D. (University of Lorraine, France) and Daniel Britt, Ph.D (Florida Space Institute, University of Central Florida, Orlando, FL)
Room 124

01:20 PM **349 - *Experimental Study on the Effects of Severe Lunar Conditions on Physical and Mechanical Properties of Lunar Construction Materials***

Aina Narvasa - San Diego State Univeristy, Marta Miletic - San Diego State University, Elisa Torresani - San Diego State University, Douglas Cortes - New Mexico State University

<u>Abstract:</u> NASA Artemis exploration program plans to establish a long-term presence on the Moon. In order to do so, repeated visits to the same location will be required and the construction of resilient and durable launching and landing pads (LLPs) will be essential. Several different in-situ lunar regolith utilization construction methods have been proposed and studied, such as sintering, grading and compacting, waterless concrete and polymer sprays, to name a few. However, despite the promising results demonstrated by certain construction methods, there remains a significant knowledge gap regarding their performance when subjected to extreme temperature variations on the lunar surface. To date, no investigation has explored the resilience of these construction methods under such extreme lunar temperatures. Therefore, the overarching research aim of this study is to fully understand the response of different LLP construction methods to the harsh lunar environmental conditions by experimentally investigating the impact of the extreme temperature variations on the physical and mechanical properties of three distinct LLP construction materials.
To accomplish this objective, the study utilized the LHS-1 lunar simulant as a base material, mimicking the regolith composition observed 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 extensive experimental results revealed that among the three methods, the SPS specimens exhibited the highest bulk density and lowest microporosity, followed by the CIP method, and finally the XG method. Consequently, the specimens produced by the SPS method showcased significantly superior macroscopic mechanical properties multiple times greater than those achieved by the other methods. However, despite demonstrating exceptional macroscopic mechanical performance before undergoing thermal cycling, the SPS specimens exhibited the most rapid deterioration in their physical and mechanical properties when exposed to thermal

loading. This degradation can be primarily attributed to their densely packed microstructure and high bulk density, which made them more susceptible to the adverse effects of thermal cycling.

Keywords: Launching and Landing Pad
Xanthan Gum
Cold Isostatic Pressing
Spark Plasma Sintering
Cyclic Thermal Loading

01:40 PM **1873 - Ice is Hot! Sintering of Ice on the Moon**

Daniel Johnson - Colorado School of Mines, Christopher Dreyer - Colorado School of Mines

Abstract: Sintering typically occurs in materials near their melting or vaporization points, which is typically considered in the context of high temperature ceramics (German, 1996). Because water ice is commonly found in nature near vaporization, melting, and sublimation curves, it can be treated similarly to metals or ceramics in terms of the sintering process (German, 1996; Blackford, 2007). Accordingly, extensive terrestrial work has been performed on the sintering of ice, particularly of snow particles over time (Blackford, 2007; Colbeck, 1997; Colbeck, 1998, 2021; Bahaloo, 2022). Ice sintering work has already been extrapolated into the field of planetary science to predict sintering time-scales for several locations in the solar system, such as Europa, Enceladus, and comets for the purpose of understanding surface and subsurface modification on these bodies (Gundlach, 2018), and was proposed as a modification process in lunar PSRs (Johnson, 2023).

Due to the granulated nature of regolith and the propensity of water ice to sinter, it is useful to consider the complex interactions and modifications between regolith and ice in the context of sintering. The wet mixing of water and regolith is a liquid phase sintering process in which rapid mass transport by the liquid phase can be achieved, and vibratory compaction prior to freezing provides advances densification. With sufficient water content, advanced total density and pore filling can be achieved. The liquid phase facilitates rearrangement and compaction of the solid phase, and once the liquid phase solidifies, further solid-state sintering can occur at a much-reduced rate to further reduce pore space. Capillary actions drives wetting and flow through the matrix. Accordingly, much higher degrees of sintering can be achieved with liquid sintering than by solid-state sintering of composite mixtures of powders with an inert component, since the inert component impedes densification.

This has been demonstrated with the novel icy simulant process PFG, which sinters ice granules and regolith together with two primary accelerators: elevated temperature (-10C to -25C), and applied pressure (Johnson, 2023). With this process, contiguous icy simulants are sintered in timescales on the order of 10 minutes. Only one component of the mixture, ice, is capable of contributing mass transport to the sintering process at these temperatures. Whether ice granules form bonds to regolith over millions or billions of years, or PFG samples are produced in a laboratory in 10 minutes, the process is fundamentally solid state sintering in both cases, but the latter case has drastically accelerated mass transport through the application of pressure.

Furthermore, sintering processes driven primarily by sublimation/deposition have a tendency to coarsen without densification (German, 1996). In this case, total surface area decreases, but pore spaces grow in size, with total porosity for the material remaining unchanged. The reduced surface energy is consumed in coarsening so that densification cannot occur. Mass transport from one surface to another (surface diffusion, sublimation-deposition, volume diffusion) provides the neck material from elsewhere on a particle’s surface, so the centers of the grains that are sintering together do not move (i.e. the bulk material does not change in density). Bulk diffusion mass transport includes grain boundary diffusion, plastic flow, creep, viscous flow) results in densification, as the centers of particles get closer together.

Keywords: Icy Regolith
Sintering
Icy Regolith Simulant
Lunar Ice

02:00 PM **2634 - An experimental study of the influence of particle size heterogeneity on seismic wave velocities**

Jules Marti - Institut de Recherche en Astrophysique et Planétologie, Université Toulouse 3 Paul Sabatier, CNRS, Santiago Quinteros - Norwegian Geotechnical Institute, NGI, Oslo, Dylan Mikesell - Norwegian Geotechnical Institute, NGI, Oslo, Ludovic Margerin - Institut de Recherche en Astrophysique et Planétologie - Université Toulouse 3 Paul Sabatier - CNRS, Pierre Delage - Ecole des Ponts ParisTech, Laboratoire Navier/CERMES, CNRS, Marne la Vallée, Naomi Murdoch - Institut Supérieur de l'Aéronautique et de l'Espace SUPAERO, 10 Avenue Edouard Belin, 31400 Toulouse

Abstract: Studying the material's elastic properties at low strains can be done by using the non-destructive technique of measuring seismic waves velocity. This technique is used for geotechnical and geophysical investigations. Thanks to the seismometers on board the Apollo [Latham et al., 1969] and InSight [Lognonné et al., 2019] missions, the velocity of seismic waves has been measured in lunar [Tanimoto et al., 2008] and Martian regoliths [Brinkman et al., 2022], i.e the entire unconsolidated cover that overlies more coherent bedrock. The grain size distribution of the lunar regolith is broader than the martian one, with 90% of the mass consisting of grains ranging from 10−5 to 10−3 m in diameter for the Moon, compared with 10−5 to 10−4 m for Mars [Isachenkov et al., 2021], [Charalambous et al., 2020]. Here, in order to better understand the in-situ seismic observations on other planetary surfaces (e.g. [Compaire et al., 2022]), we use laboratory experiments to study the role of grain size heterogeneity on the propagation velocity of shear seismic waves.
Our experiment uses piezoelectric bender elements [Dyvik and Madshus, 1985] to transmit and receive seismic waves through a cylindrical sample made up of glass beads, contained within a latex membrane. We vary two key parameters : the ratio of the diameter of the small grains to that of the large grains (i.e. the grain size ratio, GSR ∈ {0.3,0.4,0.5}), and the mass fraction of the small grains (MF ∈ [0.1,0.6]). Using CT-scans, we examine the bead distribution in our samples, which in some cases show perceptible segregation between large and small beads. Although there are small bulk density variations between samples, we show that density is not the parameter dominating velocity variations. In spite of these heterogeneous mixing, some general trends could be observed in our data. We present results from the experiments performed using glass beads at a confining pressure of 50kPa.
Three main conclusions can be drawn from our investigations. (1) The shear wave speed decreases steadily with increasing GSR. We interpret this trend as an effect of decreasing number of contacts with increasing GSR. (2) The mass fraction of the small beads also affects the seismic wave speed, but in a more complicated way, that depends on the GSR. For GSR = 0.3, as we increase MF (MF < 0.2), we first observe an increase of the seismic velocity followed by a decrease for 0.2<MF<0.4. We suggest that the former observation can be explained due to in-filling of the small beads into the gaps between the larger beads. We hypothesize that the latter observation is related to contact disruption [Choo and Lee, 2021]. For GSR = 0.5, the contact breaking effect extends down to MF = 0.1, corresponding to a decrease of velocity with MF. For MF > 0.4, the velocity increases again with MF, as the creation of contact is facilitated by the introduction of smaller beads. (3) The amplitude of the mass fraction effect is modulated by the grain size ratio. Typically, we observe that the sensitivity of the velocity to MF increases from GSR = 0.3 (6 %) to GSR = 0.5 (15%).
Our experimental results also show that seismic velocities globally increase with the frequency of the input signal, for samples with all levels of size heterogeneity tested. This supports previous

theoretical and numerical findings [Shapiro et al., 1996] that high frequencies tend to referentially sample the fast regions of the propagation medium.
We verified that our conclusions are robust against a change of pressure (e.g from 50kPa to 25kPa).

Keywords: planetary regolith
seismic velocity
grain size distribution
bender elements
binary mix
experiment

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Tuesday April 16, 2024: Afternoon Session

<u>Session Title:</u> In Situ Resource Utilization
<u>Session Co-chairs:</u> Gerald "Jerry" Sanders (NASA Johnson Space Center, Houston, TX) and Joey Palmowski (Honeybee Robotics, Altadena, CA)
Room 114

01:20 PM **2056 - *Improvements in Testing of Microwave Sintering Technology***

Alexander Madison - Florida Space Institute, Julie Brisset - Florida Space Institute

<u>Abstract:</u> NASA and government space agencies around the world are working towards bringing a sustainable human and machine presence to the Moon. Researchers across academia and industry are looking and perfecting ways to build and support a colony on the lunar surface. This includes the development of in situ resource utilization (ISRU) technology to enable the use of lunar resources and reduce the amount of supply trips from Earth. One such technology being developed is microwave sintering, which has emerged as a promising approach for utilizing lunar regolith in creating building materials.

Microwave sintering utilizes microwaves to volumetrically heat lunar regolith, offering the potential for uniform heating. However, several issues hinder its application in creating high-quality building materials. The insulative nature of regolith causes heat to accumulate in the center of the material, resulting in incomplete sintering and the formation of melt pools within the bricks. Additionally, controlling the heating process to prevent thermal runaway poses a significant challenge. Implementing a closed-loop control system could potentially address this issue.

To advance the development of microwave sintering, it is crucial to improve testing methods and materials. Most current lunar simulants lack nanophase iron and accurate lunar agglutinates, resulting in slower and less efficient heating compared to actual lunar conditions. To overcome this limitation, our lab plans to use hydrogen reduction of olivine to simulate nanophase iron and mix it into Lunar Highlands Simulant (LHS-1) and Lunar Mare Simulant (LMS-1), which are both simulants developed and sold by Exolith Lab. By creating a better analogue for microwave testing, more accurate results can be obtained, facilitating the optimization of microwave sintering parameters.

Another aspect that can enhance the microwave sintering is the utilization of a microwave resonator. A simple microwave resonator would be a metal disk with a radius ¼ of the wavelength of the incident microwave energy. For a 2.45GHz microwave this comes out to a radius of 3.059 cm. Also known as a quarter wave plate, this resonator could help homogenize the heating process, ensuring a consistent and controlled temperature distribution within the regolith. A microwave resonator would help all of the microwave energy to be absorbed. This would eliminate the reflection of microwave energy back to the magnetron, which normally causes the magnetron to overheat with continuous use. This could extend the life of the microwave system.

The integration of nanophase iron into the simulant and the implementation of a quarter wave plate hold great potential for advancing the Technology Readiness Level (TRL) of microwave sintering. These improvements pave the way for testing and improvement of microwave sintering,

leading to more efficient utilization of lunar resources, facilitating the construction of sustainable structures on the Moon.

Keywords: ISRU
Microwave Sintering
Lunar Materials
Lunar Simulant
Nanophase Iron

01:40 PM **2498 - Magnetic Separation of Lunar Regolith Simulants with Applications to In-Situ Resource Utilization on the Moon**

Peter Bachle - Missouri University of Science and Technology, Charles Wood - Missouri University of Science and Technology, Jack Vortmeier - Missouri University of Science and Technology, Rachel Adcock - Missouri University of Science and Technology, Matthew Sherman - Missouri University of Science and Technology, Jeffrey Smith - Missouri University of Science and Technology, Fateme Rezaei - Missouri University of Science and Technology, David Bayless - Missouri University of Science and Technology, William Schonberg - Missouri University of Science and Technology, Daoru Han - Missouri University of Science and Technology

Abstract: The development of in-situ resource utilization (ISRU) for metal extraction is imperative as a stepping stone for habitation construction in lunar and non-terrestrial environments. In order to optimize metal liberation from lunar ore, it is important to separate minerals by chemical composition. We designed equipment that separates aluminum-bearing minerals from iron- and magnesium-bearing minerals that constitute the lunar regolith. For the purpose of assessing a multitude of potential lunar soil conditions, we used 28 different lunar simulants that varied by mineral composition, agglutinate content, and grain-size range. The data indicate that the neodymium N52 magnets incorporated in the separation roller exhibited sufficient attraction to retain both the free iron and paramagnetic minerals while no attraction occurred for the diamagnetic minerals. Therefore, separation of the iron- and magnesium-bearing minerals from the aluminum-bearing minerals was accomplished. However, data also indicate that the fine-grained particles (105 microns and under), regardless of the composition, electrostatically bind which prevents effective separation of the paramagnetics from the diamagnetics as was demonstrated with the 500- to 250-micron and 250- to 105-micron size ranges. The agglutinate percentage did not present clear results with regard to magnetic separation. Based upon the magnetic separator results, it appears that effective separation of aluminum-bearing minerals from iron- and magnesium-bearing minerals is feasible for a particle size range of 500 to 105 microns but is ineffective for particle below this range.

Keywords: Lunar Regolith Simulants
Megnetic Seperation
ISRU

02:00 PM **2547 - Exploring Lunar Simulant-Based Geopolymers for Sustainable Space Construction: Mechanical Properties and Dynamic Analysis.**

Akm Rahman - New York City College of Technology, Nikhil Gupta - Professor of Mechanical Engineering

Abstract: The construction of habitats in space has emerged as a new hope for humankind, as it offers an alternative to human settlement apart from Earth. Exploring materials available on the lunar surface has been an ongoing endeavor, considering the high cost of transporting construction materials from Earth to the Moon. As a cost-effective alternative, researchers are exploring using materials readily available on the moon's surface, such as lunar simulants. These

stimulants are designed to mimic the composition of lunar materials, particularly those rich in aluminum and silica, potentially valuable space construction resources. Lunar simulants, created to mimic lunar surface materials, have been identified as potential resources for space construction.
Geopolymers, an inorganic material, have gained attention as a promising alternative to Portland cement. Geopolymers are composed of aluminum and silicate as base materials and undergo polymerization when reacting with alkali solutions such as KOH or NaOH. These materials exhibit fast curing and demonstrate improved mechanical properties. Therefore, this research paper explores the potential of lunar simulants as construction materials, particularly in geopolymers.
Geopolymers have shown stability and the ability to withstand high temperatures, making them attractive candidates for space construction. Adding suitable additives can further enhance their properties to achieve optimum performance. Hence, investigating the potential of lunar simulants as construction materials is the primary objective of this study.
We are investigating Lunar south pole basalt simulant on the potential to the low or zero-hydrate Geopolymer formulation that can be utilized in off or on-site autonomous construction. The purpose of this project is to evaluate the construction site environment and compositions of the south pole simulants on the overall construction process. To support this research we aim to perform a dynamic mechanical analysis (DMA) for various additives and binder ratios. DMA allows for the characterization of viscoelastic properties, providing insights into the material's behavior under different conditions.
By examining the fundamental properties of lunar simulant-based geopolymers and exploring their dynamic mechanical analysis, this study contributes to understanding their suitability as construction materials for space applications. The findings shed light on the potential of lunar simulants and geopolymers to meet the challenges of space construction, thereby paving the way for future advancements in extraterrestrial habitats.

Keywords: Lunar Basalt Simulant
Geo-polymerization
Sustainable space Habitat
Dynamic Mechanical Analysis

02:20 PM **6962 - Extraction of silica and alumina from lunar highland simulant**

Bertrand Thibodeau - Carleton University, Alex Ellery - Carleton University, Xavier Walls - Carleton University

Abstract: We present the result of a workbench experiment designed to extract silica (SIO2) and alumina (Al2O3) from the anorthosite (CaAl2Si2O8) contained in lunar regolith. Hydrochloric acid was used as a leaching reagent as it fits within a conceptual circular industrial basis for in-situ lunar resource extraction and manufacturing. A laboratory prototype was built, and commercially sourced lunar highland simulant was used to test if the non-anorthite components of the regolith would have a deleterious effect on the process.
The process involved a crude beneficiation step, followed by leaching with hot hydrochloric acid (HCl), centrifuge separation, HCl sparging, and double calcination of the final product. While silica was produced from the initial leaching, aluminium chloride hexahydrate (AlCl3·6H2O) was precipitated from the sparged supernatant. The hexahydrate was then double calcined to produce the final alumina product.
The silica and alumina that was produced could be used for the production of neutral refractory ceramics and fused silica glass, and thermal insulation fibers. By further reducing the alumina using an electrochemical, such as the Metalysis FFC process, the alumina could produce pure Aluminium metal with oxygen gas as a by-product. As for the silica produced, putting the product through a molten rock electrolysis process could produce higher purity silicon for use in early stage in-situ photovoltaic cell production.

The findings of our research demonstrated that the regolith was a good candidate for HCl leaching and the method used would make for a good candidate for lunar resource extraction using minimal Earth-sourced reagents. Overall, our research demonstrated an avenue for in-situ extraction of base materials of establish a manufacturing base on the Moon using locally sourced feedstock and minimal Earth-sourced reagents. Future research will use the lessons learned from the experiment in proposing methods of automating and optimizing the extraction process and more focus will be put on the development of physical beneficiation of the regolith to improve the quality of the extracted materials. The process used in this research produces no toxic byproducts and fits well within a near-circular industrial ecosystem where the reagents and unused products are recycled and used to carry out other extraction reactions. As we return to the Moon and plan a sustained presence there, it is critical that we approach lunar industrialization in a sustainable manner.

Keywords: In-situ Resource Utilization
ISRU
Regolith Processing
Acid processing
Lunar mining

02:40 PM **7061 - Laboratory Demonstration of Aluminium Metal Extraction from a Lunar Highland Simulant using Electrochemistry**

Xavier Walls - Carleton University, Alex Ellery - Carleton University, Priti Wanjara - National Research Council, Aerospace Research Center, Katherine Marczenko - Carleton University

Abstract: There is currently a growing interest, from both the public and private sectors, in developing technologies capable of utilizing in-situ resources in space. One of the main objectives is the Moon, since the development of such technologies would allow the establishment of a sustainable human presence there. In this project we are focusing on the potential to selectively extract Aluminum (Al) from the Moon. Not only are these materials abundant in the lunar regolith (mainly in the lunar highlands, but also present in the lunar maria), these materials could also provide great utility for a possible extended human presence.
So far, we have demonstrated that we are able to perform a selective chemical transformation to extract Silica (SiO2) and Alumina (Al2O3) from a lunar highland regolith simulant (LHS-1) by performing a magnetic beneficiation and a subsequent chemical weathering processing with concentrated (38%) hydrochloric acid (HCl). The objective of this project is to demonstrate the next step in this process, which consists in electrochemically transforming the previously produced Al2O3 into metallic Al. For this purpose, we are working on the construction of a device capable of performing an electrochemical reaction based on the FFC process. Our device consists of a water-cooled stainless-steel retort sealed with a stainless-steel lid containing feedthroughs for the electrochemical cell. The electrolysis cell consists of an alumina crucible filled with Calcium Chloride (CaCl2) as the electrolyte, a Molybdenum (Mo) cathode, and a graphite anode. An Argon (Ar) gas line and a thermocouple are also introduced into the water-cooled lid. The experiments are carried out by placing approximately 1 kg of CaCl2 into the crucible and putting around 10 g of Al2O3 into the cathode. The cell is sealed with the electrodes and thermocouple all sitting above the solid electrolyte line. Then, the temperature is ramped up to 900 °C. Once this temperature has been reached, the cathode, anode, and thermocouple are then lowered into the molten electrolyte. The current is then applied into the cell at 0.25 A ramping it up until 4 A are achieved. Reduction is allowed to take place for a period of approximately 12 h. Following electrolysis, the cathode with the product are removed from the electrolyte and are left to cool down under an Ar atmosphere. Then the sample is washed with distilled water to dissolve the salt and separate the product from the electrode. Once the product is separated from the electrode, it is placed in a funnel with a paper filter and washed with distilled water until all the remaining salt is removed

(a conductivity meter is used to verify this). The washed product is left in an oven to dry off for 2 hours. The samples are being analysed by Scanning Electron Microscopy (SEM) and Powder X-Ray Diffraction (PXRD) in order to identify the different phases in the sample. We further plan to use Additive Manufacturing to test the performance of a suite of lunar-manufacturable aluminum alloys for the construction of useful parts for the aerospace industry.

Keywords: ISRU
Moon
Aluminum

03:00 PM **9939 - THE GRIND BEGINS HERE – CRITICALITY OF PHYSICAL PRE-PROCESSING FOR SOPHISTICATED IN-SITU RESOURCE UTILISATION ON THE MOON**

Satinder Shergill - School of Aerospace, Transport & Manufacturing, Cranfield University, College Road, Cranfield, Beds. MK43 0AL. UK, Alex Ellery - Department of Mechanical & Aerospace Engineering, Carleton University, 1125 Colonel By Drive, Ottawa, ON. K1S 5B6. CA, Jenny Kingston - School of Aerospace, Transport & Manufacturing, Cranfield University, College Road, Cranfield, Beds. MK43 0AL. UK

Abstract: Lunar industrialisation will require the full gamut of technology to convert raw regolith into useful products. The early stages of physical pre-processing of lunar regolith/rock – comminution and beneficiation - prior to chemical processing in the in-situ resource utilisation (ISRU) chain is crucial. Comminution and beneficiation involve reducing raw regolith/rock into single mineral fragments and then separating them into different mineral species. These physical processes are crucial for the chemical processing phases to yield functional materials of high quality necessary to support industrialisation of the Moon. Comminution also reduces energy wasted in processing waste gangue material – it is this phase that yields the greatest amount of tailings during the concentration process – assuming 0.1% of acquired regolith is directly utilised, 10,000 tonnes of regolith must be processed to yield 10 tonnes of product. Assuming a regolith density of 1500 kg/m3, this requires regolith scooping over a 27 m radius area with a 3 m cut depth. This introduces the first trade-off in ISRU – vibratory sieving recovers a reduced fraction of regolith such that only fine-grained regolith is recovered but at a cost of increasing the regolith acquisition radius, e.g. 30% regolith recovery rate of <25 μm particles increases the regolith processing radius to 35 m (assuming increased cut depth increases cutting force to a greater degree) and the imposed additional energy of increased regolith trenching; ball-milling processes all the regolith into small particles but at the cost of increased comminution energy consumed. We shall explore this trade-off. Around 50% of the energy consumed in material processing is for these early physical processing stages - grinding is particularly energy intensive. Comminution reduces the energy requirements of subsequent chemical processing by maximizing reactant surface area but, more importantly, increases the purity of the product (such as aluminium alloy wiring) and enhances its material functionality (e.g. its electrical conductivity). Ball milling is also necessary for the preparation of sintered cathode oxides for reduction in molten salt (FFC) electrolysis in releasing metals, i.e. sieving must be supplemented by ball-milling anyway. Our preliminary planetary ball-milling (PBM) experiments suggest that full regolith pre-processing can be accomplished within 1.5- 3 hours depending on rig geometry and power, furthermore, we have shown that power requirements can be reduced by leveraging speed ratio asymmetry between rotating vials and the counter-rotating platform, at or around the critical ball ratio (rc) thereby maximising specific impact energy (Ew). Following comminution, beneficiation is necessary. There are several methods for beneficiation but only a few are suitable for the Moon. We have employed simple magnetic separation of iron species in highland regolith simulant to extract silica and alumina. However, more extensive beneficiation will be necessary to reduce impurity minerals for the extraction of functional metals including wrought metals and alloys with <0.1% impurities to ensure their functionality. Furthermore, the existence of nanophase iron renders this a more complex and challenging endeavor but introduces the possibility of microwave processing as a means of sintering necessary for cathode sintering for molten salt electrolysis.

Keywords: In-situ Resource Utilisation (ISRU)
Pre-processing
Planetary Ball Mill (PBM)
Beneficiation

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April 15 - 18, 2024; Greater Miami, FL

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Tuesday April 16, 2024: Afternoon Session

Session Title: Composite Materials for Aerospace

Session Co-chairs: Mike Fiske, Ph.D. (Jacobs Engineering/NASA Marshall Space Flight Center Huntsville, AL) and Jialai Wang, Ph.D. (The University of Alabama, Tuscaloosa, AL))

Room 126

01:20 PM **1267 - *In-plane Elasto-plastic characterization of 3K70PW Carbon Fabric/INF14 for MAT 213 material model***

Suresh Keshavanarayana - Department of Aerospace Engineering, Wichita State University,
Shritha Jagadheeswaran - Department of Aerospace Engineering, Wichita State University,
Ganesh Neta Yerram - Department of Aerospace Engineering, Wichita State University

Abstract: Laminated composites exhibit non-linear stress-strain behavior under loading modes which exacerbate the matrix stresses. The non-linearity is accompanied by residual deformations due to matrix plasticity and damage. This behavior is often modeled using orthotropic plasticity along with a non-associative flow rule.

An experimental study was conducted to develop the in-plane elasto-plastic properties for 3K70PW Carbon Fabric/INF14 at the ply level. The properties will be eventually utilized for defining the material behavior using MAT 213 material model in LS-Dyna explicit finite element software. The material characterization included the basic characterization tests under in-plane loading (tension, compression and shear) using standardized test methods. Digital image correlation was exclusively used for strain measurements during the tests. Apart from the basic elastic properties, the parameters for a non-associated flow rule were computed from the measured experimental data. Due to the fiber-reinforcement (plain weave fabric) along the two in-plane principal material directions, the material exhibited negligible plasticity under uniaxial tension and compression along these directions. However, slight non-linearity was observed under uniaxial compression loading along the two principal material directions. Under in-plane shear loading, the material exhibited significant non-linearity and residual deformation. The +/-45-deg off-axis tension and compression tests exhibited plastic deformation which was dominated by the shear responses. Surprisingly, residual deformations along the fiber directions were observed even though the axial stress magnitudes were well below the corresponding axial strength values. The test data was utilized to compute the parameters for the non-associated flow rule of the MAT 213 model. Due to the plastic deformation dominated by shear, the effective stress versus effective plastic strain associated with the in-plane shear loading was chosen as the master curve. The flow parameters were obtained by minimizing the differences in the effective stress and cumulative plastic work between the master curve and the off-axis tension and compression curves. The flow parameters were subsequently used to predict the off-axis behavior of lamina under uniaxial state of stress.

Keywords: Plastic flow rule
MAT 213
Elasto-plastic characterization

01:40 PM **7129 - A Rational Approach to Building Cohesive Zone Model for Use in Modeling Impact Analysis**

Mohammed Raihan - Arizona State University, Ashutosh Maurya - Arizona State University, Subramaniam Rajan - Arizona State University

Abstract: General constitutive models that can be used to model composite structural systems subjected to impact loads are challenging. When subjected to high impact and crush loads, composites sustain significant internal damage. This internal damage is primarily the result of delamination caused by high normal, tangential stresses and stress concentrations generated by the applied loading. Since delamination significantly reduces the structure's stiffness and strength, and often, cannot be detected because it occurs in the inter laminar layers, understanding the mechanisms of delamination is therefore essential for preventing catastrophic structural failures as well as enhancing energy absorption capabilities. Therefore, in recent decades, a significant amount of focus has been placed on the development of models to accurately predict delamination. There are three different modes in delamination - Mode I or opening mode, Mode II or shearing mode, and Mode III or tearing mode. Among these modes, Mode I, Mode II and mixed mode (derived from combination of Mode I and Mode II) occur most commonly in laminated composites. In this paper, an end-to-end process is developed for generating the material models for modeling the composite as well as the cohesive zone model using an appropriate traction-separation law (TSL). First, material properties of a common aerospace composite, IM7-8552, are obtained using laboratory testing. The obtained data are used in the MAT_213 model in LS-DYNA. Then, fracture-related tests, i.e., DCB and ENF tests, are conducted to obtain the load-displacement responses. Then using a combination of response surface methodology (RSM) and gradient-based numerical optimization technique, i.e., inverse analysis, the optimal values of the TSL parameters are obtained so that LS-DYNA's MAT_186 material model can be generated. Finally, validation of the developed models is carried out by comparing the results from FE analysis with those obtained from publicly available quasi-isotropic tension test. Results indicate that the developed process is both efficient and accurate.

Keywords: Cohesive Zone Modeling
Explicit Finite Element Analysis
Orthotropic Composites
Delamination

02:00 PM **2401 - Calculation of Stress Intensity Factors for a multiple crack-hole interaction problem**

Asif Khawaja - The University of Akron, Wieslaw Binienda - The University of Akron

Abstract: There is sufficient demand in the industry for such Ceramics Matrix Composite (CMC) models as are both computationally efficient as well as possessing sound theoretical underpinning. Stress Intensity Factors (SIF) are useful for predicting the onset and propagation of cracks, for identifying potential weak points in the design of CMCs as well as for predicting and mitigating failure modes in CMCs in the extreme air or space applications, thereby increasing their reliability and performance. Based on the work of Erdogan, Gupta & Ratwani (1973) and Binienda et al., (1992), this study intends to find a closed-form solution to the underlying singular integral equations, discretized using a suitable numerical method. The main objective presently is to study the multiple crack-hole problem and quantify & predict the onset of cracks and their growth in terms of Stress Intensity Factors. Here, the point of departure is the Bueckner's Principle which implies that the solution of this problem may be obtained through the superposition of two solutions: That of a circular hole (or elastic inclusion) inserted into a matrix without the crack, and that of a crack in an infinite, isotropic matrix, with the only external loads being the crack surface tractions which are considered to be equal & opposite to the stresses obtained in the first

problem, along the line which is the presumed location of the crack. The latter is the perturbation problem. Owing to the sufficiently large (infinite) dimensions of the matrix, the interaction between the outer boundary of the matrix and the crack−inclusion combination may be neglected in the second problem. For the first problem, an exact solution can be formulated. The Perturbation Problem is studied by means of various advanced mathematical techniques, such as deriving Complex Potentials for an Infinite region bounded by several simple closed contours, subjected to uniaxial far−field tensile loading, expressing the complex potentials as Cauchy-type integrals and writing appropriate Fredholm equations. Alternatively, the feasibility of the solution of a matrix containing edge dislocations in terms of Green's functions will be examined. The system of singular integral equations will be discretized using a suitable numerical integration method, such as Lobatto−Chebyshev collocation method, resulting in a system of algebraic equations. Written in matrix notation, the unknown function vector is determined by matrix inversion and multiplication. Thereafter, Stress Intensity Factors can be evaluated. It will also be endeavored to develop a computer code to automate the computation of SIFs. The problem is also studied in FEM environment and the effects of varying the distance between fibers and mesh size studied.

Keywords: Stress Intensity Factors
Singular Integral Equations
Lobatto-Chebyshev collocation method
Multiple crack-hole problem

02:20 PM **4678 - Advancements in the Characterization and Utilization of the MAT 213 Composite Dynamic Model**

Robert Goldberg - NASA Glenn Research Center, Trenton Ricks - NASA Glenn Research Center

Abstract: A material model has been developed which incorporates several key capabilities which have been identified as lacking in currently available composite dynamic models. The material model utilizes experimentally based tabulated input to define the evolution of plasticity and damage as opposed to specifying discrete input parameters (such as modulus and strength). The material model has been implemented into the commercially available transient dynamic finite element code LS-DYNA® as MAT 213. The model can simulate the nonlinear deformation, damage and failure that takes place in a composite under dynamic loading conditions. The deformation model utilizes an orthotropic plasticity formulation. For the damage model, the nonlinear unloading response that is observed prior to the point where the peak stress is reached can be simulated, as well as the stress degradation response that occurs after the peak stress is reached. A variety of failure models, including a generalized tabulated failure model which facilitates the utilization of general failure surfaces, have been implemented into MAT 213. Recent studies have involved examining the capability of MAT 213 to simulate the dynamic response of a variety of composite architecture subjected to a variety of loading conditions. During the development process, emphasis was given in simulating the ballistic impact response of laminated thermoset composites. Recent studies have concentrated on using MAT 213 to analyze both the impact and crush response of a variety of laminated and textile architectures. A summary of some of these studies will be discussed in the presented paper. One challenge that has been encountered by users of MAT 213 is that the coefficients of the nonassociative flow rule in the orthotropic plasticity model are extremely difficult to characterize experimentally. Users have generally applied a "trial and error" iterative approach to determine the optimal flow rule coefficients for their material of interest. In addition, the effects of the various terms of the yield function are being investigated in greater detail. A toolset and advanced characterization techniques have been developed to improve this characterization process and to make it more systematic. As part of this development process, the ability of the MAT 213 deformation model to appropriately simulate the off-axis response of composite plies have been investigated. Due to the

requirements of the orthotropic plasticity model used in MAT 213, aspects of the off-axis response have to be modified in order to ensure a consistent deformation response. The effects of these modifications will be explored in the paper.

Keywords: Polymer Matrix Composites
Impact
Constitutive Modeling

02:40 PM **4728 - Multi-Scale Experimental Characterization for LS-DYNA MAT213 Modeling of Composite Structures under High Strain Rate**

Jackob Black - Mississippi State University, Robert Goldberg - NASA Glenn Research Center, Trenton Ricks - NASA Glenn Research Center, Troy Lyons - NASA Glenn Research Center, Han-Gyu Kim - Mississippi State University

Abstract: A material model has been developed which enhances the ability to simulate the dynamic response of composite materials under loading conditions such as ballistic impact, crash, and crush. The material model has been implemented into the commercially available transient dynamic finite element code LS-DYNA as MAT_213. The model can simulate the nonlinear deformation, damage, and failure that takes place in a composite under dynamic loading conditions. The specific goals of this work are to characterize the deformation, post-peak stress degradation, and failure responses of a representative composite material with a thermoplastic matrix. The specific composite material being examined is Toray TC1225 LMPAEK T700G, consisting of T700G unidirectional carbon fibers and low-melt PolyArylEtherKetone thermoplastic resin system. The initial part of this work focused on characterizing the material parameters for the MAT_213 deformation model based on results obtained from multi-scale experimentation. The effort concentrated on characterizing the in-plane material response suitable for use with thin shell elements. For shell elements within MAT_213, tabulated stress-strain results from tension and compression tests in the 1- and 2- directions and shear tests in the 1-2 plane are required. Due to the difficulty of measuring small strains in the transverse direction, a multi-scale testing method was developed. For macro-scale testing a Shimadzu AGX-V load frame with a Basler Ace 12MP machine vision camera was used. The macro-scale testing is performed following ASTM standard test methods. On the micro-scale, a Psylotech µTS with an Olympus BXFM microscope and a Basler Ace 12MP machine vision camera was used. The micro-scale testing is performed to acquire high-resolution strain data because it is challenging to obtain high-fidelity data in transverse directions for some tests. However, the specimen dimensions must be scaled to fit into the field of view of the microscope. For both testing methods, a VIC-2D camera and software for DIC (Digital Image Correlation) analysis was used. Using the DIC combined with each test fixture, reliable stress and strain data are collected. With these data the smoothed stress-strain data, elastic moduli and Poisson's ratios required by MAT_213 are obtained. Once these data are collected, the plasticity flow rule coefficients were characterized based on full-field measurements of the evolution of plastic strain and stress fields. Single element simulations are then executed to validate that the results from the simulation match the input curves. Following this process, coupon level models for the test sets were created for analysis using MAT_213. This paper will present results from these simulations compared with previously captured experimental data to further validate the model. After the generation and validation of the MAT_213 deformation model for the material studied in this work, the MAT_213 damage model will be used to simulate the post-peak stress degradation response. The damage sub-model in MAT_213 will be validated using ballistic impact data that has been generated for this composite. Ultimately this effort aims to improve the ability to simulate the dynamic response of composite materials.

Keywords: LS-DYNA MAT213
LMPAEK Composite

Digital Image Correlation
High Strain Rate Impact
Fracture and Failure

03:00 PM **1561 - Characterization of Post-peak stress degradation of 3K70PW Carbon Fabric/INF14 for MAT 213 material model**

Suresh Keshavanarayana - Department of Aerospace Engineering, Wichita State University, Ganesh Neta Yerram - Department of Aerospace Engineering, Wichita State University, Shrtitha Jagadheeswaran - Department of Aerospace Engineering, Wichita State University

Abstract: The modeling of post-peak stress degradation or softening behavior of materials is critical to simulations where capturing material fracture is essential. Some examples include localized impacts, vehicle crash, etc. The post-peak stress degradation has been hitherto modeled based on an iterative process using higher level element tests and optimization of the degradation curves using finite element modeling. Such approaches have been found to be limited to specific laminate configurations and applications which are similar to the element tests. Fracture mechanics tests using compact tension specimens have been widely used for developing the post-peak behavior for a wide range of materials. The test data has been used to support cohesive zone models as well as smeared models based on Bazant's crack band theory. In this investigation, the post-peak responses of 3K70PW Carbon Fabric/INF14 were developed for both in-plane tension and compression loading using compact tension and compact compression specimens. The tension response was obtained based on the energy dissipated per unit crack area and the depth of the process zone. Unlike previous investigations, the process zone depth was extracted based on non-destructive inspections post-test and through strain profiles measured using digital image correlation. The fracture energy based methods do not provide an explicit definition of the post-peak response but only the area under the stress-strain curve. The stress-strain behavior is often identified using an iterative process utilizing numerical simulations to match the observed load-displacement behavior of the specimens. In this investigation, a novel approach for extracting the stress fields ahead of the crack using remote strain data was utilized in explicitly defining the post-peak stress-strain behavior. The details of this approach, its advantages and limitations will be discussed in this paper.

Keywords: Post-peak stress degradation
Crack band theory
Photogrammetry

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April 15 - 18, 2024; Greater Miami, FL

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Moss School of Construction, Infrastructure and Sustainability

Tuesday April 16, 2024: Afternoon Session

Session Title: Lunar and Martian Habitats and Infrastructure: Design Considerations and Construction Challenges
Session Co-chairs: Alexander M. Jablonski, Ph.D., P.Eng. (Carleton University, Ottawa, Canada) and Melissa Sampson, Ph.D. (Lockheed Martin Commercial Civil Space, Littleton, CO)
Room 115

01:20 PM **9178 - *Impact of Recent Lunar Missions on the Understanding of Lunar Environments***
Alexander Jablonski - Mechanical and Aerospace Engineering Department, Carleton University,
Kin F. Man - NASA Jet Propulsion Laboratory, California Institute of Technology

Abstract: Impact of Recent Lunar Missions on the Understanding of Lunar Environments
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ABSTRACT
NASA is planning to return humans to the Moon, to be followed by human missions to Mars and other destinations. It is very important to understand lunar environmental conditions as they play a crucial role in the derivation of requirements for the design and testing of lunar systems and structures. The environmental conditions on the Moon are very different from those on Earth. The Moon has negligible atmosphere, it does not possess a magnetic field, and the temperature gradient is one of the largest in the Solar System. The lunar surface is constantly being bombarded by micrometeoroids, intense solar energetic particles, and cosmic radiation. The important lunar environmental conditions include: temperature variation, radiation, lack of atmosphere and pressure, meteoroid impact, lunar gravitational field, dust, and moonquakes. All of these conditions pose a risk to lunar systems or lunar structures.

Past, on-going, and recently-launched lunar missions have had major impacts on our understanding of the extreme lunar environment. In this paper, important aspects of scientific results from the following missions will be presented: NASA’s Lunar Reconnaissance Orbiter (LRO) – launched on June 18, 2009; NASA’s Gravity Recovery and Interior Laboratory (GRAIL) – launched on September 10, 2011; NASA’s Lunar Atmosphere and Dust Environment Explorer (LADEE) – launched on September 6, 2013; China's Lunar Lander & Rover Missions: Chang’e-3 and Chang’e-4 (with the first landing on the far side of the Moon).

The focus will be on the LRO mission, which has been very successful because it has been able to collect scientific data for a significantly longer period of time than any other lunar orbiter in the past. LRO also brought a list of firsts in technical innovations, such as: first deep space precision orbit determination by laser ranging from the Earth, first global thermal mapping of a

planetary body covering a full range of local times and seasons, first bi-static radar imaging measurements from the Earth to a planetary orbiter (in this case a lunar orbiter), and first multi-beam laser altimeter system in space.

The Moon also has various geophysical features on its surface (as well as underground) that might impact design, development, and testing of lunar systems or structures. Geophysical features include: lavatubes, peaks of eternal light, and permanently shadowed areas.

This paper will conclude with recommendations for further research into lunar environments as well as identifying any missing elements of the surface environmental conditions that are important for the construction and operation of space structures on the lunar surface.

Keywords: Impact of lunar environments on lunar systems
Recent lunar missions
Lunar systems requirements
AIT requirements for lunar systems

01:40 PM **5212 - Design Approaches for Lunar Missions: Uncertainties, Risk, and Challenges in Applying Earth-based Practices**

Roberto De Moraes - AECOM ltd

Abstract: This abstract delves into the design approach for lunar missions, highlighting uncertainties, risk assessment, and challenges associated with the lunar environment. It emphasizes the need to develop specific design methodologies considering the unique conditions on the Moon, where established load and resistance factors, such as those outlined in ASCE-7, are not readily available.

Uncertainties arise when attempting to apply Earth-based design practices to lunar missions. Load and resistance factors, commonly used to ensure structural safety, cannot be directly transferred to lunar scenarios due to the absence of relevant data specific to the Moon. To address this, the abstract suggests exploring the need for an "accepted" probability of failure on the Moon, acknowledging that consequences of failure may differ for different lunar structures or systems.

The exploration phase of lunar missions serves a dual purpose: (1) identifying the lunar environment's characteristics and (2) determining the engineering properties of the Moon's surface. However, current exploration and design approaches face significant challenges due to the unique lunar environment. Factors such as low gravity, extreme temperatures, and the absence of oxygen and fluids pose distinct challenges that must be considered in the design process.

Applying lessons learned from Earth-based practices to the Moon presents additional challenges. Many established empirical observations, such as cone penetration tests (CPT), standard penetration tests (SPT), pile design, tunnel design, and rock mass classification, are based on the presence of gravity and fluids. The abstract emphasizes the need to reevaluate these practices, as the materials' behaviors on the Moon may not align with conventional conceptions influenced by Earth's gravity and fluid dynamics.

To mitigate these challenges, the abstract proposes the use of the observational method, where engineers rely on real-time data and observations during the mission to inform design decisions. This approach allows for a more adaptive and iterative design process that accounts for the uncertainties and unique characteristics of the lunar environment.

In conclusion, this abstract highlights the uncertainties, risk assessment, and challenges associated with designing structures for lunar missions. It underscores the need to develop lunar-specific design methodologies and an "accepted" probability of failure tailored to the Moon's conditions. By acknowledging the differences in consequences of failure for various lunar structures/systems and leveraging the observational method, engineers can better navigate the challenges and ensure the success and safety of future lunar missions.

Keywords: Design
geotechnical
foundation
exploration
rock mass
risks
assessment
Moon
structures

02:00 PM **5678 - Lunar Lava Tubes for Segmented Base Architectures on the Moon**

Claire Pedersen - University of Arizona - SpaceTREx, Aleksandar Antonic - University of Arizona - SpaceTREx, Farah Alqaraghuli - University of Arizona - SpaceTREx, Riley Mayes - University of Arizona - SpaceTREx, Jekan Thangavelautham - University of Arizona - SpaceTREx

Abstract: The Moon offers new resources and ease of accessibility, with its subsurface lava tubes that can provide appropriate shelter for new infrastructure. Their unique attributes make lava tubes an ideal place to house hardened shelters and refuges that would be accessed from the surface and utilized in case of any emergency. Further, the lunar lava tubes could be a repository for data that would otherwise be under threat on Earth. Utilizing a lava tube, a base could be segmented with some portions being accessible to the surface, while others are shielded by 100 m of regolith. This paper will analyze the unique contributions made possible by lunar lava tubes for lunar support facilities. Throughout this study, three lava tube structural concepts will be analyzed: a Lunar Computing and Data Center, an Astronaut Refuge & Warehouse, and a Lunar Command Center.

Keywords: lava tube
lunar base
shelter
modularity
Moon

02:20 PM **6224 - Off-World Surgical Room Construction: Minimal Design Criteria for Operating/Procedure Rooms in Off-World Environments**

Sean Mulholland - Unites States Air Force Academy

Abstract: As humanity looks towards the possibility of long-term space exploration and colonization, it is increasingly important to address the medical needs of astronauts in off-world environments. One key aspect of this is the design and construction of an operating/procedure room that can be used for non-elective/emergent medical procedures.
The unique conditions of space, including microgravity and limited resources, present significant challenges to designing and building an operating room and support spaces for use in off-world environments. In order to ensure the safety and success of medical procedures, a minimal design criterion needs to be established to facilitate the integration of medical services into off-world design needs.
There are three specific minimal design characteristics that need to be established: i) operating room size requirements/constraints, ii) MEP requirements, iii) ancillary requirements (peri-operative, storage, sterilization). A design challenge in designing an operating room for use in off-world environments is the problem of microgravity. In a microgravity environment, it will be difficult to maintain a sterile field due to the migration of particulates that are more easily handled on Earth by an engineered ventilation system. The impact of gravity on these particulates and the subsequent challenge to filter these particulates is a problem not common to Earth.

Likewise, maintaining environmental conditions suitable for surgical procedures may be an additional challenge. For example, the operating room must be able to maintain a stable temperature and humidity level, which is critical for the success of many medical procedures and a constraint on certain medical equipment. Lighting and power requirements can also be a design constraint depending on the available power and equipment used for a procedure. The room must also be designed to minimize vibrations and other disturbances that could interfere with surgical procedures.

Another challenge of designing an operating room for use in space is the limited resources available. Off-world environments will experience limitations to surgical supplies, medical equipment, and available spaces for pre/post-surgical needs. There are analogous environments on Earth, naval ships and remote research stations for example, but these environments share an ability to stabilize and transport a patient in a time period that certain off-world environments may not be able to duplicate.

Ultimately, the successful design and construction of an operating/procedure room for off-world medical procedures will be a critical step in ensuring the long-term health and well-being of extended space missions. Though short-term exploration implies a certain risk profile where medical stabilization may not be viable, longer habitation of off-world environments needs to explore how care will be provided due to the inability to transport a patient in a medically meaningful time period.

In conclusion, this paper proposes a set of minimal design criteria for operating/procedure rooms in off-world environments. The criteria consider the unique challenges of space, including microgravity and limited resources, and aim to ensure the safety and success of medical procedures in off-world environments. The proposed criteria can guide the development of future operating/procedure rooms for use in space exploration and colonization.

Keywords: Space habitat
Spatial planning
Environmental constraints
Life-support systems

02:40 PM **4185 - Defining Space Infrastructure**

Eric Wilson - Colorado School of Mines

Abstract: The words 'space infrastructure' are used frequently and widely to describe all manners of missions and programs. Knowing that the coming decades will need a wide variety of classic physical infrastructure - power and communications to name two - to new, novel infrastructure such as space situational awareness and fuel plants, this session will use an interactive smartphone app to collect survey data among the participants regarding their opinions about space infrastructure including what it is, how to classify it, and the benefits it provides. Results from the participants will be display live during the session while complete results of a wider industry survey will be published in the future.

Keywords: Space infrastructure
Classification
Participant survey
Interactive presentation

April 15 - 18, 2024; Greater Miami, FL

Tuesday April 16, 2024: Afternoon Session

Session Title: Inflatable and Deployable Structures: Applications for Space and Planetary Environments
Session Co-chairs: Sudarshan Krishnan, Ph.D. (University of Illinois at Urbana-Champaign, Urbana, IL) and Pezhman Mardanpour, Ph.D. (Florida International University, Miami, FL)
Room 117

01:20 PM **1945 - *Stability and Kinematics of Deployable Space Structures made of Scissor Linkages***

Sudarshan Krishnan - University of Illinois at Urbana-Champaign

Abstract: This paper examines the kinematics and stability behavior of deployable spatial structures of zero Gaussian curvature made of scissor linkages. Geometric design was accomplished to ensure coherent movement of parts without interference, while also ensuring minimum stowage volume. Axisymmetric structures with two and four bays and different rise-to-span ratios were analyzed. A unique snap-through behavior was observed that resulted in sudden changes in rise and span, and as such the volume – a condition that must be recognized by a designer to determine the final functional state of a structure. Stability behavior of equivalent two-dimensional models was examined using the Stiffness Probe Method. The method provided a physical understanding of the buckling behavior and related instabilities using the fact that stiffness of a structure degrades to zero at buckling. From an application point of view, the geometric adaptability of the structures may lend itself well to extreme conditions on earth as well as outer space applications such as landing rovers, among others.

Keywords: space structures
deployable structures
scissor linkages
kinematics
stability behavior

01:40 PM **3838 - Kresling Origami-inspired Structures: Exploring Structure Types, Applications, Properties, and Analysis Methods**

Hadi Ebrahimi Fakhari - Graduate Research Assistant, Department of Mechanical and Material Engineering, Florida International University, Mojtaba Moshtaghzadeh - Postdoctoral Associate, Department of Mechanical and Material Engineering, Florida International University, Pezhman Mardanpour - Associate Professor, Department of Mechanical and Material Engineering, Florida International University

Abstract: Origami-inspired structures represent a contemporary adaptation of an ancient Japanese handicraft art, utilized to create reconfigurable forms. As morphing structures, they have captured significant attention across diverse fields, leading to numerous investigations. The scholar's focus on this subject can be grouped into three primary reasons. Firstly, origami structures demonstrate remarkable versatility, featuring foldable plates, helical and conical

shapes with adjustable lengths based on the degree of folding and other variations. Secondly, these structures find practical applications in various fields, encompassing biomedical engineering, architecture, robotics, space exploration, structural engineering, and metamaterials. Lastly, the choice of origami pattern bestows distinct characteristics upon the structures.
Structures inspired by origami can be created using various origami patterns, such as Miura-Ori, Kresling, Ron Resch, Water-bomb, Flasher, and others. Each of these patterns possesses unique characteristics that make them suitable for specific applications.
Kresling stands out as one of the most renowned and practical origami patterns due to its straightforward folding and unfolding process. In this paper, we conduct an extensive review of the significant investigations conducted in the past five years concerning structures inspired by the Kresling pattern. Our review is structured into three main sections. Firstly, we delve into the various types of structures crafted using the Kresling pattern. Next, we explore the diverse applications where these structures find utility.
Origami-inspired structures find one of their most crucial applications in space investigations, primarily due to their foldability, which allows them to occupy significantly less space within space crafts compared to their unfolded configurations. This remarkable capability has made it much more feasible to transport larger structures to mission locations.
Lastly, we examine the distinctive properties exhibited by Kresling origami, including foldability, deployability, stability, fatigue life, load carrying capacity, and more. Addressing the pivotal question of how these structures are folded constitutes a crucial aspect of this paper. Notably, certain structures are self-actuated, while others necessitate folding and unfolding via an external actuator.
In the concluding section of this review paper, our focus shifts to the methodologies employed by these studies to investigate their respective subjects. Some of these papers employ experimental analyses, creating physical samples of designed structures and subjecting them to testing. On the other hand, other studies utilize software simulations to assess the influence of design parameters on origami characteristics. The software tools employed vary, with some relying on widely-used applications like ANSYS and ABAQUS, while others utilize exclusive software such as TreeMaker and ORIPA for their research. Furthermore, certain papers lean towards mathematical calculations, while others rely more heavily on Computer-Aided Design (CAD) methods.
To summarize our review, we compile a comprehensive table summarizing the various structure types, applications, main characteristics, and investigation methods presented in the selected articles for this review. This table serves as a valuable reference to encapsulate the essential findings and key aspects explored throughout the research.

Keywords: Origami-inspired
structures
space exploration
Kresling
Analysis Methods
fatigue
load capacity

02:00 PM **5097 - Fatigue Life Optimization and Design of a Reconfigurable Cylindrical Origami-Inspired Structure with Miura-Ori Pattern**

Hadi Ebrahimi Fakhari - Graduate Research Assistant, Department of Mechanical and Material Engineering, Florida International University, Mojtaba Moshtaghzadeh - Postdoctoral Associate, Department of Mechanical and Material Engineering, Florida International University, Pezhman Mardanpour - Associate Professor, Department of Mechanical and Material Engineering, Florida International University

Abstract: In this presentation, we present the design of a helical structure that incorporates multi-story origami, utilizing the Miura-Ori pattern. Our approach involves modeling individual Miura-Ori units at each vertex with carefully chosen geometric parameters. These units are then arranged in a circular pattern to construct a single story, which is subsequently replicated in a vertically upward manner to create a cylindrical reconfigurable structure. To investigate and model the folding and unfolding mechanism of this innovative structure, we employ the Finite Element Method.

In our study, we explore a range of geometrical parameters that significantly influence the characteristics of our design. These parameters encompass the length ratio (b/a), the height of each individual story, the overall height of the structure, the thickness of the facets and creases, the ratios of length and thickness for the creases, the number of single-vertices within each story, the number of stories, the pre-fold angle, the angle between the sides of the facets, and the radius of the circumscribed circle of the polygonal shape.

By varying these design parameters, we systematically investigate their impact on key structural attributes such as fatigue life, folding force, and folded volume. Notably, we identify that a crease thickness ratio (denoted as alpha) of 4 results in the highest life cycle for the origami design. Our findings reveal a significant correlation between the count of single-vertex facets in each story of the structure and the resulting levels of Von-Mises stress and strains. Specifically, the structure with the highest number of single-vertex facets experiences the least amount of stress and strains. These results underscore the importance of the configuration and arrangement of single-vertex facets in optimizing the structural performance and mitigating potential stress-related issues.

Moreover, we delve into the effects of other design parameters on the mechanical characteristics of the structure. Through our comprehensive analysis, we aim to gain a deeper understanding of the intricate interplay between these geometric factors and the performance of the origami structure.

In our research, we delve into the impact of employing various materials, each possessing distinct characteristics, on the responses of the structure. Notably, we demonstrate that the utilization of a flexible hyperelastic material for creases yields a remarkable increase in the fatigue life of the structure. Through our investigation, we aim to underscore the crucial role that material selection plays in enhancing the overall performance and durability of the designed structure.

Through our analysis, we determine the specific set of parameters that lead to the highest fatigue life, thereby ensuring the structural integrity and longevity of the design.

Furthermore, we delve into the practical applications of this exemplary structure. By highlighting its strengths and unique features, we explore potential areas where this design could be implemented effectively. Our aim is to demonstrate how the insights gained from this study can be translated into real-world applications, paving the way for innovative and efficient solutions in various fields.

In conclusion, we summarize the impact of each design parameter on the structure's response characteristics in a comprehensive table.

Keywords: Origami-inspired structures
Optimization
Miura-Ori Pattern
FEM
fatigue life
Geometric Design Parameters

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April 15 - 18, 2024; Greater Miami, FL

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Tuesday April 16, 2024: Late Afternoon Session

Session Title: The Physics of Regolith II: Mechanics, Heat, and Volatiles
Session Co-chairs: Anil Misra, Ph.D., P.E., F. ASCE (Florida International University, Miami, FL) and Adrienne Dove, Ph.D. (Florida Space Institute, University of Central Florida, Orlando, FL)
Room 124

03:40 PM **4699 - *A Framework for Application of Conditional Graphical Neural Network (cGAN)on Optimal Coordination for 3D-Printed Concrete in Extraterrestrial Environments***

Duy Hoang Pham - Center For Ai Technology in Construction, Hanyang University ERICA, Ansan, 15588, South Korea, Hyosoo Moon - Department of Civil, Architectural, and Environmental Engineering, North Carolina A&T State University, Yonghan Ahn - Department of Architectural Engineering, Hanyang University ERICA, Ansan, 15588, South Korea

Abstract: The utilization of 3D printing technology for the construction of habitats and infrastructure on celestial bodies such as the Moon and Mars presents an increasingly fascinating prospect in space construction research. The success of 3D printing constructions heavily depends on the buildability and mechanical properties of 3D printed concrete, which is influenced by various factors such as nozzle speed, interlayer interval time, RPMs of the screw, and environmental conditions. However, real-time optimizing concrete coordination could be a significant contribution to the 3D printing construction's ability when these conditions are constantly changed (Including temperature, humidity, pressure, gravity, wind speed, and so on) on other planets but still lack existing studies. Potentially, cGAN models offer advantages in terms of data-driven optimization, flexibility, cost and time savings, and handling complex relationships on optimization tasks. The objective of this study is to identify and propose a framework for feasibility assessing, identifying the data-creating approaches, and developing the application of cGAN in real-time optimizing concrete coordination. The framework involves identifying influential factors, formulating a 3D-printed concrete mix, and developing data-creating approaches specific to the extraterrestrial environment. The study result explored the feasibility of using cGAN models for real-time optimizing concrete coordination in 3D printing construction on celestial bodies. The study's main contribution lies in introducing data-driven optimization techniques that provide flexibility and adaptability to changing environmental conditions, improving the efficiency and reliability of construction in space. The application of cGAN in 3D concrete printing has the potential to contribute significantly to the advancement of construction techniques for future space exploration and colonization efforts.

Keywords: cGAN
Machine learning
3D-Printed Concrete
Optimal Coordination
Extraterrestrial Environments

04:00 PM **6722 - Exploring the Potential of Casting Lunar Regolith Simulants into Durable Materials**

Kyla Edison - Colorado School of Mines, Kevin Cannon - Colorado School of Mines

Abstract: The success of manned missions to the Moon will rely heavily on optimizing space and mass utilization. To achieve cost-effective missions, In Situ Resource Utilization (ISRU) has become essential. Utilizing the abundant regolith on the lunar surface could provide a means of manufacturing building materials required for sustaining a long-term human presence on the Moon. The lunar regolith is divided into two regions based on materials characteristics. The mare is predominantly made up of basalt and the highlands are dominated by anorthosite.

There has been a wide variety of research exploring various ways in which regolith can be utilized for building materials. These techniques include sintering, additive manufacturing and casting. Sintering and additive manufacturing have received the most attention for use in space thus far. Although terrestrial basalt casting has a long history of over a hundred years, applying this technology to lunar conditions remains an area of limited research [1]. The materials made from basalt have proven to have desirable characteristics, such as, resistance to abrasion, resistance to most acids and lye's, and impressive mechanical properties [2]. To recreate these materials comprehensive casting experiments were carried out at the Colorado School of Mines (CSM) foundry, serving as a "proof of concept" study for casting lunar regolith simulant. The primary goal of these experiments was to identify suitable molding materials, establish optimal melting and pouring temperatures, and develop an annealing schedule to ensure the production of durable and well-formed materials.

The casting experiments encompassed three main areas: 1) casting basalt and anorthosite regolith simulants, then mixtures thereof; 2) casting regolith simulant into various types of ceramic/refractory molds 3) casting molten aluminum (available as surplus from spacecraft) into a mold with silicate grains, the aluminum acts as a binding agent. So far experiments for basalt, basalt/anorthosite mix, and aluminum over silicate grains have been conducted. Due to anorthosites' high melting point of ~1,553 °C, highland-type regolith simulant on its own has not been done, we are currently underway with preparing a furnace that can reach such temperatures, and will be reported on in the final paper.

The results of the first experiments produced completely vitrified materials that would heat tear or shatter completely upon cooling. This indicated that the material was too hot and needed to cool slowly. To facilitate this slow cooling process the basalt was poured and then taken to a kiln for annealing. Annealing has been shown to significantly reduce the amount of vitrification and the number of noticeable defects.

Overall several materials have been made, and will be analyzed via X-ray diffraction and mechanical testing such as flexural and compressive strength testing.

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Keywords: Casting
Additive Manufacturing
Sintering
Lunar regolith simulants
Anorthosite
Basalt
Annealing

04:20 PM **8966 - Investigating the physical and spectral properties of icy lunar regolith for exploration and excavation**

Luke Griffiths - Norwegian Geotechnical Institute (NGI), Taeheon Kim - Norwegian Geotechnical Institute (NGI), Benjamin Lange - Norwegian Geotechnical Institute, Diana Alves de Silva - Norwegian Geotechnical Institute, Santiago Quinteros - Norwegian Geotechnical Institute, Dylan Mikesell - Norwegian Geotechnical Institute

Abstract: The ability to extract water from ice in the lunar near-surface is crucial for the future of human development on the lunar surface. Water ice has been discovered within permanently shadowed craters in the lunar polar regions, with the south pole being the target for upcoming lunar lander missions. However, to effectively extract water, it is essential to understand the composition and quantity of the icy regolith. While geophysical and remote sensing methods are used on Earth to map subsurface resources, there remains a significant gap in knowledge of the (geo)physical properties of the lunar subsurface and their link to water content. Further, excavation on the moon requires a strong understanding of the mechanical properties of the material to be excavated. The strength of the lunar regolith is expected to vary significantly with water ice content, and it is essential to determine this effect and, ideally, be able to map the strength using geophysical and remote sensing observations.

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. Based on NGI's experience testing permafrost soil in the laboratory, we established procedures for preparing icy lunar soils samples with high repeatability. Sample quality was assessed using X-ray Micro-CT imaging to ensure uniform density throughout. For each prepared sample, we performed measurements of the geophysical, geotechnical, and spectral reflectance properties of the icy lunar simulants. Cylindrical samples of icy lunar regolith simulant (Exolith Lab's LMS-1 Lunar mare simulant) were prepared 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. The P- and S-wave velocities increase with increasing ice content, while electrical resistivity decreases. Finally, Unconfined Compressive Strength (UCS) tests were conducted within a climate-controlled chamber. The strength of the material increases when the ice content is increased from 5 to 20%.

Icy samples were also prepared for hyperspectral imaging (in the ~400 – 2500 nm range), with the aim of distinguishing mineralogy as well as ice content and crystal size. 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 are being applied to the datasets to classify minerology of the pure simulant samples without ice and with various ice concentrations.

Through these experiments we demonstrate the impact of porosity and water ice content on the (geo)physical 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.

Keywords: lunar regolith
ice
geophysics
geotechnics
hyperspectral imaging

04:40 PM **9333 - Radiation Dissipation Capacity of Lunar Regolith Simulants for Efficient GCR and SPE Protection for Planetary Construction**

Kaitlin Roberts - US Air Force Institute of Technology (AFIT), Jake Branham - US Air Force, Meghan Quadrino - US Air Force Academy, Reza Aashtiani - The US Air Force Academy, Joel Sloan - US Air Force Academy

Abstract: Long-term missions on the Moon necessitate robust radiation protection measures due to the detrimental effects of radiation exposure on astronaut health. Currently, NASA imposes a 30-day exposure limit of 250 mSv for astronauts, while future missions on the Moon aim to stay below 150 mSv for a six-month duration. To achieve these requirements, this study investigates different densities of compacted regolith incorporating various ratios of additives, namely powdered polyethylene and powdered lithium hydride.
The samples were subjected to different types of lunar radiation, including Solar Particle Events (SPE) and Galactic Cosmic Rays (GCR). Analytical simulations utilizing NASA's OLTARIS tool effectively assess the shielding and transmission of radiation through the lunar regolith samples. The results show that the addition of polyethylene reduces penetration of SPEs, while the inclusion of lithium hydride reduces penetration of GCRs. Notably, the 50:50 ratio of additives provides reduced penetration for both radiation sources.
To validate the numerical simulations, a series of radiation testing were carried out at the Kirtland Air Force Base's Cobalt-60 radiation laboratory. The results demonstrate that density plays a vital role in radiation protection and dissipation mechanisms through the particulate media. The results underscored the significance of the vibration amplitude during the process of specimen compaction using the shake table in the laboratory. Evidently, increasing the vibration amplitude during the compaction process effectively reduced the dose rate, highlighting the efficacy of regolith compaction to achieve dose reduction with a constant thickness.
The research team also considered incorporation of granulated additives, at various levels, as well as layered sandwich structure comprising of compacted lunar regolith and additives. The laboratory results showed an additional layer of polyethylene offers superior radiation dissipation performance compared to samples with dispersed mixtures of granulated additives. This research provides valuable insights into the radiation dissipation capacity of lunar regolith simulants, emphasizing the significance of level of compaction of regolith with inter-layers for efficient radiation shielding in future planetary construction.

Keywords: Lunar Regolith
Simulants
Radiation
Density Simulation
GCR
SPE

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April 15 - 18, 2024; Greater Miami, FL

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Tuesday April 16, 2024: Late Afternoon Session

<u>Session Title:</u> Technologies and Approaches to Planetary Drilling and Sampling
<u>Session Co-chairs:</u> Brian Glass (NASA Ames Research Center, Mountain View CA) and Kris Zacny (Honeybee Robotics, Altadena, CA)
Room 114

03:40 PM **9384 - *DEVELOPMENT OF TRIDENT DRILL FOR ICE MINING ON THE MOON WITH NASA PRIME1 AND VIPER MISSIONS***

Kris Zacny - Honeybee Robotics, Phil Chu - Honeybee Robotics, Vince Vendiola - Honeybee Robotics, Paul Creekmore - Honeybee Robotics, Phil Ng - Honeybee Robotics, Samuel Goldman - Honeybee Robotics, Emily Seto - Honeybee Robotics, Kathryn Bywaters - Honeybee Robotics, Ezra Bailey - Honeybee Robotics, Raymond Zheng - Honeybee Robotics, Isabel King - Honeybee Robotics, Ashkan Rashedi - Honeybee Robotics, Paul Chow - Honeybee Robotics, Robert Huddleston - Honeybee Robotics, Gale Paulsen - Honeybee Robotics, Alex Wang - Honeybee Robotics, Jack Wilson - Honeybee Robotics, Jackie Quinn - NASA, Amy Eichenbaum - NASA, Janine Captain - NASA, Julie Kleinhenz - NASA, Erin Rezich - NASA, Darlene Lim - NASA, Zara Mirmalek - NASA, David Lees - NASA, Richard Elphic - NASA, Kimberley Ennico Smith - NASA, Anthony Colaprete - NASA

<u>Abstract:</u> The Regolith and Ice Drill for Exploration of New Terrains (TRIDENT) is an ice mining drill under development for two exploration missions to the Moon: Volatiles Investigating Polar Exploration Rover (VIPER) and Polar Resources Ice Mining Experiment (PRIME1). PRIME1 is scheduled to fly to the Moon in 2023 and explore the area outside of Shackleton crater, while VIPER is targeting 2024 launch year, with a goal of exploring terrain near Nobile crater. Both missions are targeting volatile rich deposits.
The primary goal of TRIDENT is to deliver volatile-rich samples from up 1 m depth to the lunar surface. Once on surface, the material would be analyzed by Mass Spectrometer Observing Lunar Operations (MSolo) and the Near InfraRed Volatiles Spectrometer System (NIRVSS) to determine volatile composition and mineralogy of the material. MSolo will fly on both missions while NIRVSS will fly on VIPER.
The Regolith and Ice Drill for Exploration of New Terrains (TRIDENT) is a rotary-percussive drill which enables it to cut into icy material that could be as hard as rock (Bar Cohen and Zacny, 2020; Zacny et al., 2022. The ice mining drill is scheduled to fly to the Moon on two missions: Polar Resources Ice Mining Experiment (PRIME1) – see Figure 1 and Volatiles Investigating Polar Exploration Rover (VIPER) – see Figure 2 (Colaprete et al., 2020, Captain et al., 2016).

<u>Keywords:</u> Drill
Moon
ISRU
Water

04:00 PM **1334 - TRIDENT Drill Validation Testing in Haughton Crater, Devon Island, Canada**

Brian Glass - NASA Ames Research Center, Carter Fortuin - Honeybee Robotics, Thomas Stucky - NASA Ames Research Center, Isabel King - Honeybee Robotics, Hashem Battah - NASA Ames Research Center

Abstract: The Honeybee TRIDENT drill that is going to the Moon in late 2023 (PRIME-1) and will be on VIPER (late 2024) has not yet been tested in impact crater permafrost. Apart from thermal vacuum tests with simulants, a past SMD PSTAR tested a TRIDENT engineering unit drill in Chile's Atacama desert (the ARADS project) in 2017-19. However, the Atacama is a hot, hyperarid analog site with relatively soft sediments (good for testing life-detection instruments but not a good lunar polar or Mars analog for drilling and sampling). The TRIDENT drill was not noticeably stressed in these field tests.

Prior to lunar operations, risk-reduction argues for drill testing at a higher-fidelity analog site. Haughton Crater is a ~22 million year old impact crater, with both subsurface ice (permafrost near the surface), no ground cover, and regolith (impact fall back breccia, in massive exposed bedding). The SETI Institute manages an accessible field camp annually as the Haughton-Mars Project (HMP).

Past prototype drill tests 2004-2016 at the Haughton Crater analog site have focused on testing the mechanical and software controls performance of successive planetary prototype drill designs. A baseline of past drill design performance data exists for the site. The DAME drill was tested here in 2004-2006 and 2008; the CRUX drill in 2009-2010 and 2016; the Icebreaker-1 drill in 2011-2012; LITA/Icebreaker-2 in 2013 and the updated Icebreaker-3 in the summer of 2014. In addition to verifying and validating the electromechanical performance of a TRIDENT drill unit in icy impact breccia, field testing also validates the current build of NASA Ames-developed AI-oversight automated drill control software, including planning, diagnostic and fault recovery capabilities.

In July/August 2023 a NASA/Honeybee Robotics team will deploy a TRIDENT drill to Haughton Crater and test it in a series of boreholes drilled on "Drill Hill", a massive breccia deposit inside the crater. The season test goals included: drilling multiple boreholes past the active (surface thawed) layer into subsurface ice layers; demonstrate icy-regolith AI fault detection and safing/recovery pertinent to at least four (of six) known major TRIDENT drilling fault modes; correlate drill performance (energy, rate of penetration) with the material type and characteristics of the layer(s) penetrated in sequence; and provide clean subsurface samples to collaborating researchers. Initial drilling hardware and software validation test results are presented.

Keywords: planetary drilling
AI and robotics
analog sites
Haughton Crater

04:20 PM **1128 - Drilling for Lunar Surface Exploration and Shear Strength Evaluation Based on Drilling Information**

Byunghyun Ryu - Korea Institute of Civil Engineering and Building Technology, Jangguen Lee - Korea Institute of Civil Engineering and Building Technology, Jin HyunWoo - Korea Institute of Civil Engineering and Building Technology

Abstract: Prospecting ice on Moon requires drilling systems to obtain subsurface samples and measure composition of ice deposits. Landers and rovers need to be equipped with drilling equipment in order to analyze the ice and subsurface resources located at the poles of Moon. These devices must be small, lightweight, low-power, highly efficient and high-performance units in order to function properly under the extreme conditions of the lunar environment. Researchers have developed a prototype drilling apparatus that is able to operate in atmospheric and cold environments. Newly developed drilling system in Korea, which is capable of performingnot only sampling but also subsurface investigation, is introduced.

Keywords: Drilling system
Strength
Drilling information

04:40 PM **7493 - Optimization of bio-inspired drill design for lunar exploration**

Liang Zhang - University of Cincinnati, Lei Wang - University of Cincinnati, Quan Sun - University of the District of Colubmia, Qiushi Chen - Clemson University, Jesus Badal - University of the District of Colubmia

Abstract: In recent years, many nations have launched lunar exploration missions. Characterization of the lunar regolith is critical for the extraction and utilization of the in-situ resources to build a permanent base on the Moon. However, due to many challenges for drilling operations on the Moon, higher demands have been placed on the drilling tool design on the moon. Designing an optimal lunar drill and determining its controlling strategies become crucial to the research on the lunar regolith. This paper presents an optimization design framework for the clam-inspired drill design into the lunar regolith based on the discrete element method and multi-objective optimization. The parameters for the discrete element modeling are calibrated using the triaxial tests conducted on the lunar highlands simulants (LHS-1) using the Taguchi method. The burrowing process of the razor clam is used in the design of the drill into the lunar regolith and a discrete element modeling of clam-inspired drilling is then built. A new design optimization framework is proposed for the clam-inspired drill into the lunar regolith. In the first stage, the design parameters of the drill geometry (i.e., anchor height, anchor shape, and cone apex angle) are optimized and the design objectives are construction cost and total power consumption for the drilling. A multi-objective optimization is used to identify the most preferred geometry design for the drill. With the most optimal geometry adopted in the second step, the controlling strategies (i.e., downward velocity, rotation velocity, expansion velocity, and anchor-cone distance) are investigated in the design space, and the drilling effectiveness and drilling efficiency are evaluated as the two design objectives. With the obtained optimal geometry design, the controlling strategies (i.e., downward velocity, rotation velocity, expansion velocity, and anchor-cone distance) are investigated in the second stage. The drilling effectiveness and drilling efficiency are evaluated as the two design objectives in the second stage, and the optimal controlling strategies are realized following a similar optimization procedure. The proposed design optimization framework can provide an efficient and optimal solution for the design of bio-inspired tools and technologies for lunar exploration.

Keywords: Optimization
Drill
Regolith
Lunar Exploration

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April 15 - 18, 2024; Greater Miami, FL

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Tuesday April 16, 2024: Late Afternoon Session

Session Title: Engineering, Construction, and Materials Concepts for Resilient Deep Space (Lunar and Martian) Infrastructure
Session Co-chairs: Jibu Abraham (JHU Applied Physics Laboratroy-APL, Laurel, MD) and Gerald "Jerry" Sanders, Ph.D. (NASA Johnson Space Center, Houston, TX)
Room 115

03:40 PM **4164 - *Control Towers as Navigation Beacons for Lunar Surface Construction Operations***

Sivaperuman Muniyasamy - University of Arizona - SpaceTREx, Athip Thirupathi Raj - University of Arizona - SpaceTREx, Min Kang - University of Arizona - SpaceTREx, Jekan Thangavelautham - University of Arizona - SpaceTREx

Abstract: NASA's Artemis initiative aims to restart crewed missions to the Moon. These planned crewed lunar landings have sparked interest in continuously occupied lunar surface outposts. However, maintaining a sustained human presence on the lunar surface at a larger scale than ever before comes with challenges. First, due to the difficulty of sending large numbers of human astronauts to the Moon and supporting them, robots will be used for tasks such as infrastructure construction and in-situ resource utilization (ISRU) on these outposts, called lunar bases. Additionally, to deliver necessary supplies to human astronauts on the Moon, regular landings must be made by supply spacecraft. Precision navigation infrastructure is required to manage autonomous systems on lunar bases effectively, as construction robots need to find their position on the Moon, and landing spacecraft must be able to land on designated landing areas for the safety of the astronauts.
The existing literature has suggested options for positioning, navigation, and time (PNT) on the Moon. NASA and ESA have proposed putting communication and navigation satellites in Lunar orbit, similar to global navigation satellite systems (GNSS) on Earth, with expected errors of approximately 10m. For more precise positioning required for construction equipment and spacecraft landing, previous studies have proposed the use of landers on the lunar surface as radiofrequency (RF) navigation beacons inspired by VHF omnidirectional range (VOR) and distance-measuring equipment (DME) radio beacons used at airports on Earth, or as reference stations for differential positioning using satellite navigation. Another study has proposed using self-deployable masts in support of lunar surface operations. These masts can support multiple functions at the same time, including communications, navigation, and power transmission, and have the advantage of having unobstructed lines of sight to users on the Moon's rough terrain.
We extend the existing work by examining the performance of navigation beacons mounted atop self-deployable towers. Specifically, we first find the optimal placement of these towers, with considerations for lines of sight to users on the ground and dilution of precision (DOP). Optimizing the placement of these towers includes finding requirements for the height of the towers necessary to have unobstructed lines of sight. Furthermore, we design methods for our array of towers to find the initial positions of themselves and each other, helping increase accuracy by reducing bias. Second, we verify the feasibility of and design a deployment mechanism that allows

the payload to reach the required height while reducing the construction cost. Using structural analysis, we test whether the deployable structure can reach the required height and whether the deformations and vibrations of the tower degrade the positioning accuracy below acceptable bounds. We also use Monte-Carlo simulations to validate the navigation performance under vibrations and structural deformations.
In this study, we propose and design a network of towers for use as beacons for the localization of robots on the lunar surface. We extend the existing body of work on navigation for the lunar surface using beacons by examining the requirements in placement and structural design of the physical structure required to implement such a system and validating the feasibility of meeting these requirements.

Keywords: control tower
rovers
Moon
navigation
communications

04:00 PM **2560 - The Role of Earth Anchors in Space (Space Anchor)**

Hamed Niroumand - Gdansk University of Technology, Lech Balachowski - Gdansk University of Technology

Abstract: Earth anchors are essential elements for installing various structures into the ground. They can play a major role in Space. Space agencies aim to develop a new life on the Moon and Mars, which requires buildings for future cities. Existing earth anchors are used in two systems: grouting and mechanical. Mechanical anchors, such as plate, helical and irregular shaped anchors as keying, are used in different applications on Earth. Future buildings need foundations, and earth anchors can install different buildings and structures on the Moon and Mars. However, it is not as straightforward as on Earth projects, because the Moon and Mars have very different conditions. The advancement of earth anchor technologies is an advantage, but space anchors need more research and development. Based on these requirements and gaps, this review paper focuses on various types of earth anchors that can evaluate the feasibility, challenges and opportunities of earth anchors in space.

Keywords: Earth anchor
Space Earth-Anchor
Moon
Mars
Space
Space anchor

04:20 PM **6357 - An ontology to represent and combine multi-disciplinary design knowledge for lunar habitat design, deployment, and maintenance**

Arne Martensen - Buro Happold Berlin, Timo Hartmann - Technische Universität Berlin

Abstract: Future permanent lunar habitats will be complex engineered systems that need to support closed ecological systems that provide safe and healthy conditions for space colonialists. The design process of lunar habitats is therefore characterized by a high number of requirements with respect to ecological functions, human health and safety considerations, and structural as well as physical constrains for building in space. While the existing literature has developed some initial concepts for lunar habitat design, an explicit and systematic representation of knowledge domains for habitat design is missing. To work towards such a systematic knowledge representation, this paper presents an ontology that organizes and integrates information related to lunar base systems design. The developed ontology explores key concepts, relationships, and properties relevant to lunar habitats, namely concepts related to the lunar environment, concepts related to habitats, and concepts related to human well-being. Combining these concepts, the ontology provides a structured representation of knowledge to support various applications, including conceptual as well as detailed systems design, system deployment, and system maintenance. Moreover, the combination of concepts that the ontology provides can support the multi-disciplinary efforts that are required for the above listed applications. Methodologically, the ontology was modeled along four key steps: Requirements analysis, conceptualization, ontology design, and evaluation. All development steps were based on a review of the existing literature about lunar based design. The paper introduces and describes the ontology and discusses the practical implications of the developed ontology highlighting its potential applications in lunar base research and development. Additionally, we will provide a detailed discussion of required future steps for improving, but also validating the ontology. Finally, the paper will present an outlook of how ontological approaches form the basis for the systematic design of lunar habitats in terms of providing the basis for integrated simulation approaches combing models for ecological, health and safety, and structural assessment. Furthermore, the outlook will also discuss how ontological approaches are required for habitat deployment and maintenance.

<u>Keywords:</u> habitat design
ecology
health and safety
structure
ontology

04:40 PM **1674 - Filtration Challenges and Approaches for Space-based Oxygen Recovery Systems**

Gordon Berger - USRA, Juan Agui - NASA

<u>Abstract:</u> As space missions are planned to last longer and move further away from Earth, technologies to recover oxygen from metabolic carbon dioxide must be improved and developed. Resource recovery of both oxygen and hydrogen is necessary for exploration missions to succeed without continuous and extensive resupply. Even at high efficiency, the gas reactions including Bosch and Sabatier that have been developed to close this supply loop produce varying amounts of solid carbon that can foul oxygen recovery reactors and other life support system components. While particulate matter filters have a long track record of success on NASA space systems, oxygen recovery systems impose strict filtration requirements due to the continuous output of carbon particulates that necessitates autonomous and periodic regeneration of the filter to recover capacity. Additional challenges including restrictive size and weight, variable cabin pressures, multiple gravity environments, limited power budgets and long operational lifetimes must be taken into consideration when designing filtration systems. These challenges and technologies that have been tested will be discussed in this presentation.

<u>Keywords:</u> Filtration
Life Support
Particulate Matter
Oxygen Recovery

05:00 PM **6075 - Spacecraft Filtration Investigations in NASA's Specialized Analog Filter Test Stands**

Juan Agui - NASA Glenn Research Center, Gordon Berger - USRA, R. Vijayakumar - Aerfil

Abstract: NASA seeks to advance air filtration concepts for future space exploration missions. To support this goal, NASA has established core capability and expertise in Environmental Control and Life Support Systems (ECLSS) air filtration at the Glenn Research Center (GRC) including setting up unique laboratory filtration test stands in the Particle Filtration Laboratory and developing novel patented technologies. These filter testing stands are adaptable to different filter applications to readily meet the changing mission needs of the agency, tailoring them most currently to meet the Artemis program requirements. The Artemis program will require filtration of lunar dust in spacecraft habitable volumes. One of these test stands, a horizontally oriented recirculating filtration flow loop (named the "Lunar Filtration Flow Loop") is considered a unique filter testing platform within NASA and throughout the filtration industry for testing small filter test articles. While providing features and amenities like those found in industrial filter testing facilities, it also provides the capability to test with lunar simulants and to operate at sub-ambient pressures representative of lander or orbiter cabin atmospheres because of its recirculating closed-loop operation. The Lunar Dust Filtration Flow Loop has been used multiple times to provide test services for several in-house projects and was also adapted to support the flight experiment Mars Oxygen In-Situ Resource Utilization Experiment (MOXIE). A smaller test stand with a vertically oriented open-loop design was set up to test the ISS Bacterial Filter Elements (BFE) which are long aspect ratio HEPA filters, and named the BFE Test Stand. The test procedure used with BFE Test Stand have been adapted into the latest IEST (Institute of Environmental Sciences and Technology) HEPA filter test standard (IEST-RP-CC001.7) for long aspect ratio filters. Most recently, a new recirculating Vertical Filtration Flow Loop has also been built to provide the same essential capabilities and features of the earlier flow loop but provides better distribution of the particle flow, less particle losses, and most importantly allows the testing of full-size filter elements. This more recent flow loop has supported several major projects and programs such as the Human Land System (HLS) and the Gateway Habitation and Logistics Outpost (HALO). Highlights of these specialized test stands and the tests performed will be presented.

Keywords: Filter
Lunar dust
Test stand
Flow loop
ECLSS

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Moss School of Construction, Infrastructure and Sustainability

Tuesday April 16, 2024: Late Afternoon Session

<u>Session Title:</u> Lunar and Martian Geotechnics and Foundation Design
<u>Session Co-chairs:</u> Pooneh Maghoul, Ph.D. (Polytechnique Montréal QC, Canada) and Roberto de Moraes, P.Eng. (AECOM, Oakland, CA)
Room 117

03:40 PM **1501 - *Preliminary analysis of regolith-foundation-structure interactions***

Tomasz Adach - International Space University, Thomas Dylan Mikesell - Norwegian Geotechnical Institute, Samuel Ximenes - Astroport Space Technologies, Miranda Fateri - Aalen University, Aidan Cowley - European Space Agency

<u>Abstract:</u> Reliable foundations are critical when it comes to building secure and resilient structures in the lunar environment. Without these crucial components, the sustainable infrastructure for lunar resource exploration would be compromised, posing risks to human life and necessitating higher levels of maintenance. Nevertheless, our current knowledge and ability to address technological construction challenges, including the interactions between foundation-structure and lunar regolith, the behaviour of lunar regolith under static or dynamic loads, and lunar seismic activity, still have limitations.
The preliminary analysis identify the potential static and dynamic infrastructure loads, and simulate lunar regolith elastic deformation subjected to static loads. Dynamic loads are approximated using static equivalents. It analyses various geotechnical shoring systems necessary for the lunar resources exploration:
- launch, Landing Pad (LLP),
- storage facilities or shelters,
- supporting infrastructure,
- surface habitats.

It should be noted that the above-mentioned components are primarily intended to be constructed using In-Situ Resource Utilization (ISRU) and on-site manufacturing, as outlined in various space agency roadmaps. This approach involves shaping the regolith through processes such as sintering and melting using 3D printing techniques.
The objective at this stage is to quantify crucial geotechnical parameters and analyse the behaviour of lunar regolith under exploitation loads, in order to inform structural design decisions. The key parameters considered in this research include:
- load-bearing capacity of the lunar regolith,
- magnitude and orientation of downward forces,
- average and differential settlement of the soil.

To investigate lunar soil stress and deformation, an initial analysis is conducted using finite-element models to simulate the elastic behaviour of the ground. Both 2D and 3D models are employed for this purpose. Subsequently, the obtained results are analysed in terms of soil bearing capacity and serviceability limit states. The calculations are based on assumptions derived from the mechanical properties of lunar regolith samples and extrapolated using regolith analogues, noting the limitations when comparing analogue materials to actual lunar regolith.

The outcomes of this research include :
- enhancement of analytical modelling of lunar regolith-structure interaction,
- estimation of lunar soil deformation under imposed loads,
- identification of the most adapted type of ISRU based foundations,
- enhanced understanding of the limit states and lunar geotechnical risks.

At this stage this research aims to emphasize the significance of lunar geotechnics and make contributions to the advancement of lunar structural design, foundation construction, and reinforcement of lunar regolith under the structure using In-Situ Resource Utilization (ISRU). Future research could focus on the structural impact of thermal loads and space weathering, as they constitute important factors that have not been fully addressed in this study.

Keywords: Civil Engineering
Foundation Design
Geotechnical Analysis
Lunar Infrastructure
Regolith-Structure Interaction
Risks Assessment
Soil Deformation
Structural Design

04:00 PM **3518 - Compaction testing on lunar highland simulant using a vibrating drum roller**

Akshay Kumar Agarwal - The University of Adelaide, Mark Jaksa - The University of Adelaide, Brendan Scott - The University of Adelaide, Yien Lik Kuo - The University of Adelaide

Abstract: NASA is soon to send astronauts to explore the Moon near the lunar South Pole, which is predominantly composed of lunar highlands regolith. Understanding the lunar ground is an essential aspect of this endeavor. This study presents the results of laboratory testing involving a 1:13 scale model of a vibrating drum roller compactor incorporating a lunar highland simulant. Surface settlements, earth pressures and densities were measured to quantify the extent of improvement. The results demonstrate that the technique is effective in compacting the near surface regolith simulant. Further studies are required to determine the most effective travel speed and frequency of vibration.

Keywords: Surface compaction
Earth Pressure cells
Density
Surface Settlements

04:20 PM **9136 - Preliminary Guidelines for Geotechnical Site Investigation and Site Preparation for Construction of Lunar infrastructure**

Pooneh Maghoul - Polytechnique Montreal, Roberto de Moraes - AECOM, Nathan Gelino - Exploration Research & Technology Programs, Kennedy Space Center, NASA, Peter Carrato - Bechtel Corporation, Matthew Waterman - Bechtel Corporation, Ramesh B. Malla - UNIVERSITY OF CONNECTICUT

Abstract: The success of every ground-based construction project, whether on Earth or the Moon, strongly depends on the robust foundation design and the capacity of foundation soils to withstand external loads in the short-, mid-, and long-term. Considering uncertainties and unknown unknowns in an unknown world in the geotechnical design of lunar infrastructure is of paramount importance. Hazards are inevitable, however, building substantial infrastructure without understanding the physical and mechanical properties of lunar regolith can result in structural failure due to soil failure. Furthermore, early infrastructure on the Moon will be most

likely composed purely of regolith such as berms/blast protection, flat and hazard (rock) free operational areas, and improved trafficability pathways. Hence, the ability to manipulate regolith and create "regolith works" to meet geotechnical requirements is a fundamental first step for installing infrastructure for a sustained presence.
As such, the mechanical behavior of the foundation soils on the Moon (lunar regolith) or Moon rocks plays a key role in designing lunar structures such as landing/launch pads, tall communications/power towers, pipelines, building foundations, anchors, trenches, and so on for human settlement on the Moon. Our current understanding of the ability of lunar regolith/rock to support infrastructure and the conditions of the Moon's surface is limited to data acquired during past missions, which precludes comprehensive characterization of the near-surface conditions on the Moon. To develop regolith works and human establishment initiatives, the implementation of a consistent and methodological approach to determine the geotechnical properties for a safe landing and sustainable construction is critical.
In this paper, we aim to provide some preliminary guidelines for site preparation and investigation for Moon exploration to ensure the safety and success of missions to the lunar surface. The main goal is to address a crucial aspect that has been absent in existing site selection frameworks: the geotechnical and engineering geology conditions of the landing site. We will cover all aspects of site preparation and investigation, including site characterization, terrain analysis, technology development required for geotechnical investigation on the moon, and site preparation. The guidelines are comprehensive and ensure that all relevant factors are taken into consideration.

Keywords: Lunar infrastructure
Geotechnical design
Site investigation
Site preparation
Technology development

04:40 PM **9744 - Crushing Potential of Lunar Regolith Simulants: Implications for Strength Degradation**

Reza S. Ashtiani - United States Air Force Academy, Jesus Baca - The University of Texas at El Paso

Abstract: This study presents an in-depth geotechnical analysis of lunar regolith simulants, with focus on particle breakage behavior—an essential factor for future lunar exploration and colonization. Twelve NASA-provided simulants representing diverse lunar regions underwent extensive experimentation. Tests included varying deformation rates, relative densities, overburden pressures, and densification methods to replicate lunar surface conditions. This paper specifically investigates particle breakage behavior under normal and shear loads for two selected simulants. Results bear significant implications for lunar missions and infrastructure development. Engineers can apply these insights to design structures capable of withstanding lunar conditions, ensuring missions safety and sustainability. Our comprehensive approach advances understanding of regolith simulants, paving the way for robust engineering solutions in lunar exploration and colonization. This research represents a critical stride towards harnessing the Moon's potential for scientific exploration and long-term human presence.

Keywords: Lunar regolith
Compaction
Shear strength
Dilatancy
Non-linearity

05:00 PM **8191 - Towards Ground Motion Estimation Model Development for Mars**

Dewan Mohammad Enamul Haque - PhD Student, Planetary Science Lab, LSU Geology & Geophysics, Suniti Karunatillake - Associate Professor, LSU Geology & Geophysics, Juan M Lorenzo - LSU Geology & Geophysics

Abstract: Based on Insight findings, Martian seismology primarily focuses on exploring seismicity and interior structure. Less attention is given to ground motion estimation model development & site amplification estimation. However, ground motion is important to assess the engineering demand for near-future human settlement-related infrastructure design. Peak ground acceleration, fundamental site frequency, fundamental site period, corner frequency, and attenuation are essential design parameters. In this ongoing research, we are developing ground motion estimation models for Marsquakes and impact events separately.

Among recorded Martian seismic events, several events have characteristics similar to terrestrial tectonic earthquakes. Especially, Cerberus Fossae is seismically active (Sun & Tkalčić, 2022). Most shallow earthquakes are found here as low-magnitude and high-frequency (HF) events (Perrin et al., 2022). The character of low-frequency events suggests a potentially warm source region consistent with recent volcanic activity at shallow depth (Stähler et al., 2022). The HF marsquakes occur in the brittle shallow part and might originate in the fault planes associated with the graben flanks (Stähler et al., 2022). Sita et al. (2022) explain that these diverse faulting mechanisms from different locations represent intra-crustal deformation in the form of volcano-tectonic quakes related to magmatic activity.

Since Mars is still believed as a single plate (e.g., Sun & Tkalčić, 2022), we attempt to develop a ground motion model considering intra-plate settings. Intra-plate ground motion model development requires information about the magnitude, stress drop, hypo-central distance, corner frequency & Vs30 information. Ground motion model will be developed for selected Marsquakes & impact events with excellent quality Insight recording (Mars Insight Events) and the lowest distance/depth related uncertainty. A generalized ground motion model exhibits three predictor variables, i.e., magnitude, hypocentral distance, and Vs30 representing the source, path, and site effects. We retrieved the magnitude and distance information from the Marsquake catalog (Mars Insight Events). Recently, (Hayashida et al., 2023) developed a method to estimate Vs30 from horizontal over vertical spectral ratio (HVSR). Vs30 can also be estimated by fitting the theoretical H/V curve with the experimental one (Castellaro & Mulargia, 2009). The coefficients and error will be estimated through regression analysis (Efron & Tifshirani, 1994).

So far, we estimated PGA for the Insight recorded the largest Marsquake (s1222a) (Kawamura et al., 2023) & impact (s1000a) (Posiolova et al., 2022). We have analyzed the largest Insight recorded s1222a Marsquake and impact event s1000a for data quality & frequency content check, converting velocity into acceleration. Moreover, we have estimated the corner frequency for these two significant events. Additionally, we will estimate site amplification at the Insight location using ambient noise horizontal to vertical spectral ratio. We will estimate a site's resonance frequency and the fundamental period from ambient noise measurement's horizontal-to-vertical spectral ratio (HVSR). Recently, (Cox et al., 2021) developed an approach (hvsrpy) for single station-based HVSR measurement. Our initial results show that the s1222a event is characterized by higher PGA & lower attenuation compared to s1000a.

Keywords: Ground Motion Estimation
Mars
Marsquakes
Martian Impact Events
Engineering Design Parameters

05:20 PM **4328 - Bearing capacity estimation in nonlinear granular deposits under reduced gravity field: lunar applications**

Reza Jamshidi Chenari - Royal Military College of Canada, Pooneh Maghoul - Polytechnique Montreal

Abstract: Conventional estimation of bearing capacity relies on three main contributors: cohesion, unit weight, and overburden pressure. In granular materials, gravity has a dual influence on bearing capacity. The first contribution comes from passive resistance, which is influenced by the weight of the foundation soil. Additionally, gravity indirectly affects the load bearing behavior of granular soils by influencing the stress-dependent stiffness and strength parameters. Given the expected low gravity on the moon's surface, where future superstructures might be established, lunar soils have undergone repeated pulverization, condensation, and mixing due to cosmic collisions and exposure to solar wind over extended periods. Even today, these soils continue to change through meteorite impacts and interactions with high-energy solar and space charged particles. Despite the lack of comprehensive research into the constitutive behavior of lunar soils, it can be assumed that the frictional lunar surface soils may exhibit nonlinear behavior, influenced by stress. This study aims to explore this effect by using the Finite Difference Method (FDM) analyses in FLAC. It assumes a stress-dependent nonlinearity for the foundation soil while reducing the gravity level to one-sixth of Earth's. The results will shed light on how estimating bearing capacity on lunar soil might differ from terrestrial contexts and offer insights into adjusting conventional bearing capacity equations for lunar construction purposes.

Keywords: Lunar geotechnics
Foundation design
Bearing capacity
Probabilistic analysis

Wednesday April 17, 2024: Morning Session

Session Title: Regolith Simulants I
Session Co-chairs: Jason Schuler (NASA Kennedy Space Center, FL) and Daniel Johnson (NASA Kennedy Space Center, FL)
Room 124

10:20 AM **5053 - *Optimized development of lunar regolith ceramic with reduced content of sodium silicate***

Usman Javed - Curtin University, Faiz Shaikh - Curtin University

Abstract: Lunar regolith is a potential source of raw materials for in situ resource utilization for the development of lunar habitat. The recent discovery of molecular water on the lunar south pole opened research venues for the development of the lunar binder. However, reducing the water demand for developing lunar binders is a major challenge. In this study, we explore the possibility of using sodium silicate as a fluxing agent to lower the sintering temperature and enhance the mechanical properties of lunar regolith ceramics. We use two types of lunar regolith simulants: LHS-1, which represents the lunar highlands, and LMS-1, which represents the lunar mare. The lunar highlands, mare, and mixture of both were prepared by adding 15, 20, 25% sodium silicate and subjected to a sintering temperature of 1200˚C. The strength development was assessed by compressive strength and microstructural analysis including Scanning Electron Microscopy and X-ray Diffraction. The results indicated that the ceramic synthesized with the combination of both lunar highlands and mare regolith simulant yielded higher compressive strength than both individual lunar highlands and mare regolith ceramics. Therefore, synthesizing lunar ceramics demands the lowest water content and offers promising benefits.

Keywords: Lunar regolith
Molecular water
Lunar ceramic
Sodium silicate
Sintering

10:40 AM **9582 - Lightweight Lunar Regolith Simulant for Lunar Regolith Operations Studies**

Mehran Pourakbar - New Mexico State University, Marta Miletic - San Diego State University, Douglas Cortes - New Mexico State University

Abstract: Lunar surface simulation materials and facilities have far-reaching implications for both robotic and human exploration. Future lunar missions can be designed and operated more effectively by gathering essential data through laboratory studies on Earth. It is one of the main objectives of these studies to achieve greater safety, efficiency, and success in extraterrestrial exploration. One of the significant challenges that lunar missions face is the interaction between surface regolith and construction equipment. The low gravity on the Moon plays a significant role in machine-regolith interaction. With only about one-sixth of the gravity on Earth, the forces acting on the wheels are significantly reduced. Vehicles may encounter reduced traction and slippage as a result, making lunar travel more challenging. The ideal simulants should possess mechanical properties (shear strength and stiffness) like those of lunar regolith while also exhibiting reduced weight. Thus, allowing for mechanical testing to proceed under a 'reduced' gravity during normal laboratory testing on earth. This paper introduces a lightweight simulant, named M-LMg, that is made by mixing recently developed lunar simulants from New Mexico State University. M-LMg simulates lunar Mare regolith and contains ultra-lightweight aggregates derived from recycled glass. The unit weight of the simulant is controlled by adjusting the percentage of lightweight material in the mixture. A series of laboratory tests were conducted to measure various geotechnical properties of M-LMg, including specific gravity, grain size distribution, minimum and maximum bulk densities, friction angle, P-wave velocity, and thermal conductivity. The relationships among bulk density, porosity, thermal conductivity, and P-wave velocity were investigated for lightweight simulants under both Earth's atmospheric pressure, and vacuum. A comparison of the properties of M-LMg with lunar regolith and other well-known simulants shows that the lightweight simulant generally meets the required mechanical properties at small and large shear strains at a fraction of the weight. Overall, the development and characterization of M-LMg represents an important advancement in lunar surface simulation, and it is expected to serve as a fundamental tool for conducting regolith operations physical modeling studies on Earth.

Keywords: Reduced gravity
Regolith simulant
P-wave velocity
Thermal conductivity

11:00 AM **6044 - Laser particle sizer for lunar-lander dust plumes**

Robert Peale - University of Central Florida, Nagendra Dhakal - Truventic LLC, Cameron Kelley - University of Central Florida, Dinidu Hathnagoda - University of Central Florida, Christian Walker - University of Central Florida, Phillip Metzger - Florida Space Institute/UCF, Chris Fredricksen - Truventic LLC, Adrienne Dove - University of Central Florida

Abstract: Surface dust blown by a lunar lander threatens operations and assets. To aid prediction and protection, we are developing a lander-mounted laser-based instrument to obtain empirical particle-size distributions in ejecta plumes. The particle size distribution is to be determined from laser propagation decay at multiple wavelengths. We present laboratory experiments to confirm theoretical expectations for laser propagation decay constants for independently known particle size distributions. We used sub-micron particles of TiO_2 suspended in water or micron-sized particles of ZnO suspended in glycerin. Their particle size distributions were determined independently by a dynamic light scattering apparatus. Calculated decay constants, determined from an integral over size of the product of geometrical cross section, Mie scattering efficiency factor, and size distribution, agree with experiment within the statistical uncertainty for the measurements. The method of solving the inverse problem to determine the desired size distribution from measured decay constants will be illustrated and discussed. For laboratory experiments more closely relevant to the application, we are dropping showers of ~10 micron diameter lunar simulant particles or 200 micron glass beads or sand in an evacuable chamber and imaging the laser propagation through these clouds. For the lunar simulant, we are applying ellipsometry to determine average optical constants needed for Mie scattering calculations. Similarly, we are imaging laser beam propagation below the surface in open bodies of water to advance technical readiness of system hardware in the presence of multiple environmental interferences. Progress on a prototype for tethered rocket tests, as well as automated methods to reduce rapidly-acquired images to decay constants for calculation of temporally and spatially varying particle size distributions, will be presented.

Keywords: Plume surface interaction
particle size distribution
laser particle sizer
lunar lander

11:20 AM **7408 - RIDER: A World-Class Facility in Planetary Terramechanics Investigations**

Jared Long-Fox - University of Central Florida, Michael Lucas - University of Notre Dame, Gabriel Blandin - University of Central Florida, Michael Conroy - University of Central Florida, Joshua Conway - University of Central Florida, Abigail Glover - University of Central Florida, Austin Hacker - University of Central Florida, Clive Neal - University of Notre Dame, Daniel Britt - University of Central Florida

Abstract: Safe and efficient mobility is a fundamental requirement for planetary exploration, resource utilization, and any infrastructure development. Incomplete testing during research and development of planetary mobility systems poses significant risk to mission success. Gaps in testing can arise from improper materials (wheel materials or regolith simulants), improper preparation of those materials (compaction to match target environments, worn simulants), insufficient understanding of wheel-regolith interactions over fresh and previously trafficked surfaces, longevity testing of wheels and other rover components, and improper environmental conditions (e.g., gravity force and atmospheric). There are currently no commercially available test facilities available to properly test rover wheels and their interactions with planetary regolith; therefore, the Center for Lunar and Asteroid Surface Science (CLASS) at the University of Central Florida, in collaboration with the University of Notre Dame, created and has made available the Regolith Interactions for the Development of Extraterrestrial Rovers (RIDER) testbed.

RIDER subsystems include a 3.8 m long, 0.9 m wide, 0.5 m deep regolith bin, simulant compaction equipment, dust mitigation systems, illumination and video recording systems, a load application/gravity offloading system, air filters and industrial dehumidifier, programmable brushless DC motors with different gear ratios, electronics control and data logging system, and a system to allow any rover wheel from 26 to 82 cm in diameter to be mounted on RIDER. RIDER is housed at the UCF CLASS Exolith Lab, providing access to world-class simulant production facilities that enables researchers using RIDER to request, purchase, and utilize custom lunar, Martian, or asteroid regolith simulants. The geomechanical and analytical expertise of CLASS researchers is also available to RIDER customers to help quantify travel efficiency and traffic-induced changes to regolith simulant physical properties and rover wheels.

Dust mitigation is a paramount concern in rover operations both on planetary surfaces and in the laboratory; RIDER was developed with a negative pressure system, air filters, sealed doors, and barriers to protect mechanical systems and electronics. The environment on planetary surfaces is drastically different than that of Earth as surface are often in or close to vacuum, with the regolith generally desiccated and effecting the terramechanical properties of the regolith or regolith simulant (Long-Fox et al., 2022). Therefore, RIDER was developed with an industrial dehumidification unit to help minimize moisture in the air and in the simulant. RIDER also has customizable illumination and video recording systems. The control system allows RIDER users to input wheel size, desired, speed, and gravity-adjusted single-wheel rover mass (up to 200 kg as of Summer 2023) to test wheel-regolith interactions by driving the wheel back and forth across the simulant a given number of times. Data on rotation speed, linear travel rate, motor current, wheel sinkage, and applied normal load (simulated rover mass) are logged to comma-delimited ASCII text files. The initial test campaign of RIDER (GATOR, Lucas et al., 2023) used a replica LRV wheel, VIPER-like Resource Prospector wheel, and a prototype Astrobotic Polaris wheel. This work details the RIDER system at the time of writing, design considerations, and upcoming refinements.

Keywords: Trafficability

Rovers
Moon
Mars
Testing
Mobility
Analog
Simulant
Terramechanics
Rover Wheels
Testbed

Wednesday April 17, 2024: Morning Session

<u>Session Title:</u> **Space Construction, Habitats and Structures**
<u>Session Co-chairs:</u> Nathan Gelino (NASA Kennedy Space Center, FL) and Mark Hilburger (NASA Headquarters, Washington DC)
Room 114

10:20 AM **5694 - *EUROHAB Secondary Habitat - A potential European contribution to ARTEMIS***

Peter Weiss - SPARTAN SPACE, Makthoum Peer Mohamed - SPARTAN SPACE, Nisheet Singh - SPARTAN SPACE, Thibaud Gobert - SPARTAN SPACE

<u>Abstract:</u> The ARTEMIS Program intends to set the basis of a sustainable human presence on the Moon as steppingstone towards Mars. Various nations have joined this endeavour which was initiated by the United States under NASA leadership. A potential non-US contribution could be a so called “Secondary Habitat” which is brought to the lunar surface by a robotic lander. Such a habitat can be positioned on the surface at a strategic site where it can be used as an exploration outpost by a human crew that is arriving later. This kind of infrastructure would allow to bridge the gap between safe human landing sites and sites of interest in permanently shadowed regions, the lunar Far Side or crater rims which are permanently exposed to sunlight. The habitat would arrive by a robotic lander, without crew, and therefore needs to comply to the constraints of payload capacities.
This paper describes the development of EUROHAB which can be brought to the lunar surface by a European lander such as EL3 ARGONAUT our NYX. EUROHAB was developed as a size-one mock-up in 2021 in cooperation between several entities. A follow-up study financed by the French CNES allowed to study the system design in more detail and to adapt the dimensions of such a habitat as payload to a robotic lander. The paper will discuss various aspects of the habitat design: energy production and storage, ISRU and robotic resupply of oxygen, and concepts of operations. The roadmap towards such a development, with a target towards the end of the ARTEMIS horizon in 2030, will be illustrated.
EUROHAB could be a contribution to the US-led effort to build up a sustainable presence on the lunar South Pole.

<u>Keywords:</u> Secondary Habitat
Inflatable Habitat
ARTEMIS

10:40 AM **9698 - Advancements in Extraterrestrial Infrastructure Construction using Microwave-Processed Regolith and Minerals**

Aleksandra Radlińska - Penn State, Peter Collins - Penn State, Sven Bilén - Penn State

<u>Abstract:</u> Microwave energy has great potential to advance extraterrestrial and terrestrial construction technologies, as lunar regolith–based concrete materials, specifically geopolymer concretes, can undergo an initial rapid cure through microwave radiation and metal ores can be

smelted into components that can be used for reinforcement. In this work, research has been conducted to develop technology for processing in situ regolith with microwave energy to formulate lunar construction material. Since water serves as a mixing medium in geopolymer concrete, microwave energy can assist in controlled and rapid water removal and acceleration of geopolymer formation. Our work to date has shown that samples were able to undergo an initial cure using a conventional household inverter microwave by cycling its lowest power level (~125 W). In between each cycle, the sample had a rest period to cool down. Without a rest period, a level of outgassing would be reached that would become detrimental to the material by causing severe cracking or rapid expansion. By monitoring the temperature of the sample, optimal power levels and lengths of microwave application time can be obtained. This work will discuss research conducted to determine the optimal parameters as a function of sample size and a new high-power microwave system developed to enable sample processing of both regolith and metal ores. The new microwave applicator enables the accurate measurement of delivered microwave power and focuses the microwave energy within the cavity to increase overall system efficiency.

Keywords: lunar construction
regolith
microwave curing

11:00 AM **6165 - APPLICATIONS OF FUNDAMENTAL CONSTRUCTION PLANNING FOR LUNAR BASES**

Kyle Foley - Texas A&M University, Patrick Suermann - Texas A&M University

Abstract: NASA's Artemis mission plans to return to the Lunar surface in the coming years with the goal of re-establishing a "Moon to Mars (M2M)" manned presence using remotely controlled or autonomous construction equipment. NASA has released their blueprint to mission accomplishment and outlined objectives critical to success. This paper will further investigate the requirements and criteria for evaluating efficacy of potential solutions, primarily by focusing on the approach to planning. This will be explored by using components of critical path method, a scheduling technique used in the construction industry that is effective for navigating uncertainty. Criteria will include planning, using assumptions, comparing solutions, analyzing risk, and interoperability. This paper will also propose a logical progression of objective development to accomplish the mission of lunar colonization as an example to begin further discussion.

Keywords: Regolith
Lunar construction
Critical path method
Lunar inhabitation
Lunar economy

11:20 AM **7146 - Re-evaluation of the Design of Buried Structures as Lunar Habitats under Extraterrestrial Loads**

Parisa Haji - Chief Technology Officer, Matrix Engineering & Trading Ltd. (MET)

Abstract: The concept and the design of buried structures under various loadings on Earth such as highway live loads and even seismic blast loads are well regulated with a satisfactory accuracy in standard such as AASHTO and Canadian Standard Association (CSA). With Artemis mission, promising the return of humans on the moon, a buried structure can provide a living and working habitat for astronauts. In this research, first, the minimum required size of a pipe-arch shape buried structure is identified based on surveying the past astronauts working in International Space Station (ISS). The buried structure is then designed under the loads effective from moon's extreme environment. Finite Element Analysis (FEA) has been conducted to study the behavior of buried structure under load variations and to re-evaluate the past theories and formula. The conclusion to the results of the study is presented as how some design codes can be revised for buried structure application in extreme environment.

Keywords: Buried structure
lunar habitat
extreme environment
Finite element analysis
Design standards

11:40 AM **1117 - Development of an in-situ sample reception and pre-analysis facility for a secondary habitat on the lunar surface**

Peter Weiss - SPARTAN SPACE, Serge Chevrel - IRAP, Yves Daydou - IRAP, Makthoum Peer Mohamed - SPARTAN SPACE, Nisheet Singh - SPARTAN SPACE, Thibaud Gobert - SPARTAN SPACE

Abstract: Thirteen potential landing sites on the lunar south pole have been identified for the ARTEMIS III mission. The south pole of the Moon hosts a variety of different sites of interest and its exploration by human astronauts will go hand in hand with robotic exploration. But this new era of lunar exploration differs from every past mission: they all target the same region and equipment, or items can therefore be handed over from one mission to another. This scenario offers the possibility to build-up an infrastructure of equipment and facilities in proximity towards a sustainable presence on the lunar south pole.
The paper presents the design of a sample reception and analysis facility integrated into EUROHAB which is a secondary habitat that can be brought as a payload to the lunar surface via a European robotic lander. Such a habitat could serve as rallying point between different human and robotic missions, and thus serve to receive geologic samples that are collected by robotic scouts or astronauts. These samples could be analysed before transporting them to Earth: Weight and volume constraints for sample return could result in a significant delay in studying the samples. This would constitute a significant obstacle to the advancement of science and for testing the use of materials as resources for a sustainable presence on the Moon. A requirement would be to select the samples to be returned in priority to Earth. It therefore would be a strong interest to develop an on-site pre-analysis platform which allows an autonomous examination of samples and a deeper assessment of their scientific relevance to either determine whether they should be transported to Earth (immediately or by a consecutive mission) or discarded. The paper will present the development of such a facility and first tests in a terrestrial mock-up.

Keywords: ARTEMIS
Samples
EUROHAB
Geology

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April 15 - 18, 2024; Greater Miami, FL

FIU | Engineering & Computing
Moss School of Construction, Infrastructure and Sustainability

Wednesday April 17, 2024: Morning Session

Session Title: Coastal Resilience Under Extreme Weather Conditions
Session Co-chairs: Landolf Rhode-Barbarigos, Ph.D. (University of Miami, Coral Gables, FL) and Othman Oudghiri-Idrissi, Ph.D. (University of Michigan, Ann Arbor, MI)
Room 126

10:20 AM **6632 - *Aerostructural UAV main rotor optimisation algorithm considering mass and strength limitations***

Jakub Kocjan - Military University of Technology Warsaw, Stanisław Kachel - Military University of Technology Warsaw, Robert Rogólski - Military University of Technology Warsaw

Abstract: The latest earth and space researches altered the possible operations that can be conducted by the UAV. The requirement of structures that are capable to provide better features for various reconnaissance operations is observed by national authorities and manufacturers . Hence, a tools that are able to provide rapid design and evaluation of new UAV solutions and improvements are needed. This work presents the next stage of the studies, where all of the methods that were separately evaluated and adjusted to the main rotor design needs, are combined to provide a comprehensive aerostructure optimisation. The proposed algorithm is based on parametric modelling of the shape and structure rotor blade, and the fluid enclosures. The fully parametrized model is shown to be used in each step of the optimisation procedure as a best solution for evaluating various blade configuration in reasonable time. The presented algorithm is combining the latest solutions for aerostructure researches. It starts with parametric preparing of the models using CAD software, which are applied to CFD and CAE environments. The separate environments are linked to provide an FSI solution for blade aerostructure analysis and to obtain the performance parameters. All of the procedure is arranged as a loop to find the best solution. The objective function in optimisation procedure is proposed, as well as the decision variables that will be altered. The results are evaluated with analytical calculations of obtained optimal results.

Keywords: UAV
optimisation
rotor
aerostructure

10:40 AM **7404 - Investigation on the Pressure Distribution of Buildings with Irregular-shape Plans**

Manuel Matus - Florida International University, Ioannis Zisis - Florida International University

Abstract: Major economic and human losses have been attributed to extreme wind events such as hurricanes and tornadoes in the US (NOAA, 2023). Researchers have extensively studied the impact of these natural occurrences on civil infrastructure bolstering the resilience of constructed environments and the establishment of building code standards and wind provisions, such as ASCE

7-22 (ASCE). Advancements in society, materials, architecture, and construction techniques have led to the evolution of structures, moving away from traditional squared and rectangular shapes. Additionally, there is a growing emphasis on maintaining harmony between structures and their natural surroundings, resulting in the design of buildings that adapt to and coexist with nature (Lehman, 2011; Konior, 2022). Present building codes and wind provisions play a crucial role in ensuring the safe design of structures. However, it is essential to acknowledge that these guidelines were formulated almost 50 years ago based on wind tunnel testing performed on regular-shaped models (Akins et al., 1977, Davenport et al., 1977 and Stathopoulos, 1979). A variety of investigations have been carried out to assess the effect of wind induced forces on structures with complex shapes. However, the vast majority have been aimed at mid- and high-rise structures (Gomez et al., 2005, Mashalkar et al., 2015, Souvik et al., 2014, Yi et al., 2016, 2017 & 2020, Zhao et al., 2017, Rajdip et al., 2016, Rajabi et al., 2022) leaving a lack of understanding regarding low-rise structures with irregular plans, buildings that represent 70% of our modern built environment (Stathopoulos et al. 1993, Zhang et al. 2014, Parackal et al. 2016, Shao et al. 2019, Uematsu et al. 2022, Verma et al. 2022, and Sarma et al. 2023 and Potter, 2020). An investigation was undertaken to examine low-rise structures featuring intricate designs. These unique shapes were derived by analyzing satellite images of residential areas in South Florida. The analysis revealed that among the most popular shapes were T, C, L, and S configurations. Ten models (1 to 100 scale) were created and produced using 3D printing technology and tested at the Wall of Wind (WOW) at Florida International University (FIU). Out of the ten models, eight possessed irregular shapes, consisting of four with gable roof ends and four with hip roof ends. The remaining two models were rectangular in shape, with one featuring gable roof ends and the other showcasing hip roof ends. Initial findings indicate that complex flow interactions between non-uniform shape sections lead to intricate pressure development in walls and roof sections. As an example, windward walls will experience varying positive pressures based on the existence of an attached sidewall that protrudes in the upwind direction, forming a 90-degree wall joint. Surprisingly, these sidewalls, anticipated to encounter negative pressures, were found to experience positive pressures due to intricate flow interactions. Furthermore, the wall and roof sections exhibit surprising pressures development, differing from those observed in rectangular models. Overall, buildings with irregular shapes tend to exhibit higher suction pressures on their walls, while their roof sections undergo higher positive pressures.

<u>Keywords:</u> Irregular shape
low-rise
pressure distribution
codification

11:00 AM **8038 - Mega Project- Modification of DEZ Dam Power Plant Intake, based on the Spinal Cord Innovation Simulation Design through Submerging of Steel Rings**

Afshin Turk - construction, structure, Geo-technical eng, Syed Mahmood Ahmed - Department Head of Building Construction Science, College of Architecture, Art & Design, Mississippi State University, Shabnam Ghanavatizadeh - biologic, environmental eng, Khuzestan Green Plain Watch Association, NGO's.

<u>Abstract:</u> Nominal reservoir volume of DEZ Dam is 3 200 000 000 cubic meter with capacity 520 megawatts. Water intake is located at least 80 m under the normal water level of reservoir that shall transfer the fresh water into the power plant with 8 unite 65 MW. After 60 years, upstream current transports a huge sediment behind the dam that can be occupied the volume of reservoir (65 percentage of total height). Water intake has been situated in the critical conditions by sedimentation particles incoming. Simulated steel box body will be moved slowly to set on the right wing rock from platform to intake. The new intakes will be set in 40 m and 60 m under the normal level. Sensitive part of project is referred to reptile moving of simulated biologic steel box

on the concrete slots. In comparison, biologic innovation design will cost less than 2 000 000 US ⁄ 30 000 000 US.

After 60 years, upstream catchment area erosion will cause to transporting a huge amount of sedimentation near the power plant intake level (+266.5 m). This manner can be very hazardous for turbine fans cavitation and shafts that system will alarm to shut down the power plant. Drawing sheets and as built maps can provide the better vision of intake transition tunnel (270.0 m to 280.0 m) and longitudinal sections. Gate section guide, were executed by the 4 concrete slots on the right wing rock from platform (354.0 m) to vent line of intake (282.0 m) with 78 m length. Segments steel box will be simulated to drop back on the constructed concrete slots (1959) by cliff nailing and grouting on the rock. It is mentioned that structural support must be stabled to pass the two flexible steel box (600 + 600) 1200 tons gradually motion. Simulated steel boxes must be nailed on the cliff surface and concrete gate guide (1959). This operation must be implemented in the next year in depth 60 m to extend aging of power plant at least 40 years. Extension time may be guaranteed the utilization of Power Plant until 2065 that can be remove the hazardous of intake sedimentation. This project seriously needs the semi-ellipsoid steel shell with rectangular section (a=1 800 cm, b=1 000 cm, h=1 000 cm and t= 5 cm) that must be set accurately in the trash rack center-line in level 266.5 to 283.2 m (in depth 80 m). Based on the momentum forces, the two new intakes (levels: 290.0 m and 310.0 m) will be installed to replace with old intake (level 270.0 m). Grouting nuzzles will be install in the flexible steel box bed to provide injection nailing into concrete gate guide slots. Semi- ellipsoid shell should be fixed on the transition tunnel around the corner of trash rack by injection into the rock surface. Significant; Simulation of reptile motion can be obtained to be fixed on the rock surface by segment boxes and movable joints, Artificial Intelligence Designing –AID- may be defined by the steel box segments and movable joints that each connection are allowed to move in two degrees freedom, rotation and longitudinally. In 2021, Governments come to a decision of new replacing tunnels above the power tunnel outline, DEZ 1431 (1959) with budget 50 000 000 US 3 years duration and 1.5 Safety Factor. In comparison, biologic innovation design will estimate the total cost less than 2 000 000 US, 1 year duration and 8.0 Safety Factor. Spinal cord simulation will take an effectiveness by above computation more than 180 times.

Keywords: water intake of power plant
biologic reptile simulation
innovation steel design

11:20 AM **3156 - A Sustainable and Efficient Structural Solution for Hybrid Coral Reefs**

Sandesh Lamsal - Dept. of Civil and Architectural Engineering, College of Engineering, University of Miami, Gustavo Aguilar - Dept. of Civil and Architectural Engineering, College of Engineering, University of Miami, Peisen Tan - Dept. Of Ocean Sciences, Rosenstiel School of Marine, Atmospheric, and Earth Science, University of Miami, Gerald Clark - Rosenstiel School of Marine, Atmospheric, and Earth Science, University of Miami, Brian Haus - Dept. Of Ocean Sciences, Rosenstiel School of Marine, Atmospheric, and Earth Science, University of Miami, Landolf Rhode-Barbarigos - Dept. of Civil and Architectural Engineering, College of Engineering, University of Miami

Abstract: Coral reefs dissipate wave energy providing vital protection to coastal regions. The loss of a mere top one meter of the reef results in disastrous flooding along the coastline. With corals being at risk of extinction due to climate change, water quality and diseases, hybrid coral reefs, which consist of human-made structures populated with corals, promote restoration efforts while providing coastal protection. This study focuses on a modular perforated reef design based on SEAHIVE, a sustainable and efficient revetment system developed at the University of Miami (UM). The design's ability to reduce wave energy and create habitats is investigated by conducting scaled

physical testing at the UM Alfred C. Glassell, Jr. SUSTAIN Laboratory (SUrge-STructure-Atmosphere INteraction) and pilot studies.
Preliminary tests reveal that the proposed perforated design performs better than its solid counterpart regarding wave energy reduction. The design's perforations also enhance macro-scale complexity, which increases habitat creation potential. To better understand the importance of the reef's morphology, two different reef configurations based on the same number of SEAHIVE units were tested. The first is based on two rows of nine units, while the second includes three rows of six. The results show that the configuration of two rows of nine units dissipated 10-30% more wave energy than the configuration of three rows of six units, depending on the hydrodynamic conditions. This finding emphasizes the importance of selecting an appropriate reef configuration for specific coastal conditions. Exploring the flexibility of the modular design which can be adapted to various coastal wave conditions combined with physical testing can enhance the system's performance and long-term stability. This study contributes thus to the implementation of a novel green engineering alternative for shoreline protection that preserves and restores our valuable coastal ecosystems.

Keywords: Coral reefs
Hybrid reefs
SEAHIVE
Morphology
Wave-energy dissipation
Habitat
Green engineering

11:40 AM **3532 - Investigating hurricane-induced wind and wave loads through scaled physical testing**

Gustavo Aguilar - Dept. of Civil and Architectural Engineering, College of Engineering, University of Miami, Sandesh Lamsal - Dept. of Civil and Architectural Engineering, College of Engineering, University of Miami, Peisen Tan - Dept. Of Ocean Sciences,

Abstract: Tropical cyclone-induced winds, waves and storm surges continue to devastate communities, causing damage and casualties in coastal regions around the world. In US cyclone-prone regions such as Florida, engineers often follow the ASCE/SEI 7-22 Minimum Design Loads and Associated Criteria for Buildings and Other Structures manual to ensure a safe built environment. Nonetheless, Hurricanes Ian's (Cat4., 2022) and Michael's (Cat 4., 2018) aftermath show evidence of major structural damages in areas where waves and storm surge were significantly high, suggesting that the modeling of the combined effect of winds, waves and storm surge may need to be revisited. With the 2021 Emergency Event Database (EM-DAT) report showing that the number of storms, the intensity of storms, and the frequency of the more intense storms are increasing, the damage and casualties from the coupling of wind and flood loads will get worse, which is further exacerbated by climate changes.
This study consists of physically testing different building models of local typologies subjected to individual and coupled wind, wave, and storm surge loads. Testing will occur in the Alfred C. Glassell, Jr. SUSTAIN Laboratory (SUrge-STructure-Atmosphere INteraction), a wind-wave tank simulator capable of generating up to 155 mph winds, directional waves, and surges. However, proper scaling for coupling wind and flood loads is always challenging. For this goal, mean wind speed profiles and turbulence intensity profiles of SUSTAIN are being developed using different wind and wave conditions at various locations along the length of the tank aiming to correlate mean wind speed profile and water surface roughness at different fetch along the length of the tank. The changes in the mean wind speed profiles and surface roughness will ensure proper scaling of the winds, waves, and building geometry for testing the building models. This project's

findings can potentially improve coastal structures against tropical cyclones by providing a better understanding on the coupling between wind and wave loads.

Keywords: Hurricane
Wind
Storm surge
Wave action
Coupling
Experimental testing
Scaling

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Wednesday April 17, 2024: Morning Session

<u>Session Title:</u> Structures under Extreme Environments: Theory and Applications

<u>Session Co-chairs:</u> Wei Zhang, Ph.D., P.E. (University of Connecticut, Storrs, CT) and Bin Xu, Ph.D. (Huaqiao University,
Quanzhou, China)
Room 128

10:20 AM **4825 - *Origami Infrastructure: A Viable Solution to Construction for Challenging Environments***

Claudia Calle Müller - Florida International University, Alvaro Ballon Bordo - Unaffiliated, Mohamed Elzomor - Florida International University

<u>Abstract:</u> Infrastructure built in challenging environments should be able to withstand unforeseen climate and environmental challenges, including extreme temperatures, high winds, severe rainfall, and natural disasters. Most importantly, dwellings should provide humans with a safe, livable, and resilient shelter. To this end, construction materials, design solutions, and construction processes must be considered to ensure safe and livable conditions. Furthermore, technology and innovative means of construction must be explored to reinforce infrastructure resilience and sustainable performance. However, previous literature has not addressed which features and materials are most adequate for resilient, deployable, and cost-effective origami shelter structures. This research aims to fill this gap by (1) identifying the suitable materials and features of structures that have been proven to be effectively deployable in such challenging environments through literature review; and (2) proposing and analyzing the viability of origami infrastructure as a solution to construction obstacles in challenging environments. Origami is rapidly emerging in science, engineering, and construction applications as deployable and reconfigurable engineering systems of all scales that can be fabricated with a wide variety of materials. Origami structures are geometrically versatile, adaptable, and can be easily and quickly assembled. Moreover, they are lightweight and foldable, which facilitates their transportation into challenging environments where access can be difficult and limited. Therefore, origami structures present an innovative, sustainable, resilient, and feasible solution to construction obstacles in challenging environments. The findings of this study serve researchers and construction stakeholders who will be designing and building infrastructure systems in challenging environments.

<u>Keywords:</u> Origami Infrastructure
Challenging Environments
Construction
Infrastructure for Challenging Environments
Resilient Infrastructure
Sustainability

10:40 AM **6906 - Livability Index for Residential Homes in a Changing and Extreme Climate Condition**

William Hughes - National Institute of Standards and Technology, Wei Zhang - University of Connecticut, Zhiqing Li - University of Connecticut, Steven Matile - University of Connecticut

Abstract: To make the residential homes livable, various civil infrastructure systems, such as residential buildings and systems, power and water systems, and transportation systems, are providing their functionalities to support community residents' daily lives. With projected future changes of climate conditions, the risk to residential homes and their associated civil infrastructure systems has greatly amplified. Many residential homes could be damaged or disrupted, leading to uninhabitable homes and communities during or after extreme weather conditions due to climate change. To evaluate and quantify the living condition for residential communities, a livability index is proposed to integrate various vulnerabilities of civil infrastructure systems that could negatively impact community residents' daily lives. To demonstrate the proposed livability index, a case study is conducted for a coastal community in the state of Connecticut, which is under a future extreme weather scenario in the year of 2100. Two potential future representative concentration pathway (RCP) climate change scenarios, RCP2.6, and RCP8.5, are considered alongside uncertainties in the future climate's effects. Under such a framework, it is possible to evaluate the benefits of different resilience options to improve the community livability so as to reduce the damaging impacts to the community residents from future changing and extreme climate conditions. The proposed livability index concept could also be extended to evaluate future interstellar community when subjected to different extreme conditions and threats. These findings can help inform enhanced adaptation strategies to improve community resilience.

Keywords: livability index
changing climate
infrastructure systems
community resilience
residential
building vulnerability
power distribution fragility
transportation fragility

11:00 AM **1969 - Building shape effect on wind induced torsion, shear, and lift for low-rise structures.**

Hrishikesh Dev Sarma - Florida International University, Ioannis Zisis - Florida International University

Abstract: The wind vulnerability of low-rise buildings has been a subject of concern as both the envelope components and the wind load resisting structure can be damaged due to the forces induced during an extreme wind event such as a hurricane or a tornado. Despite the prevalence of non-rectangular buildings especially in the residential building stock, wind induced loads on non-rectangular low-rise buildings is a less explored topic with a scarcity of data and literature. In this study, the phenomenon of wind-induced torsion, lift and shear forces on low-rise buildings is explored. Wind tunnel tests were performed on a series of gable roofed and hip roofed low rise buildings. Each building model is tested in an atmospheric boundary layer wind tunnel for twenty-four wind directions, i.e., 0^{o} to 345^{o} at 15^{o} increments. The pressure data obtained from the wind tunnel tests is used to evaluate torsion, base shear and lift coefficients on the buildings. Five different shapes are considered for the analysis, four of which are non-rectangular, i.e., L-shaped, T-shaped, C-shaped, and S-shaped buildings, along with one control model which is rectangular in shape. The directional variation of each wind load coefficient obtained from the non-rectangular models is compared with that from the rectangular model. The critical wind direction with respect to each building shape and load coefficient is evaluated. The results obtained from the analysis reveal significant differences in wind loads due to the differences in shapes and provide recommendations regarding provisions for wind design standards.

Keywords: Wind Loads
Low-rise structures
Irregular shaped structures
Wind resistant design

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Wednesday April 17, 2024: Morning Session

Session Title: Architecture on the Moon and Mars: Designing for Human Space Exploration
Session Co-chairs: Olga Bannova, Ph.D., Lic.Eng. (SICSA, University of Houston, Houston, TX) and Romolo S. Capitanio (European Space Agency-ESA, Warmond, Netherlands)
Room 117

10:20 AM **891 - *Moonfiber: Design of a lunar lavatube outpost using regolith--composite fibers***

Vittorio Netti - University of Houston, Paolo Mangili - University of Houston, Alessandro Angione - Politecnico di Bari, Ivana Fuscello - Politecnico di Bari, Isabella Paradiso - Politecnico di Bari

Abstract: The recent efforts to return to the lunar surface embodied by the development of the Artemis program include the concept of achieving a permanent stay, enabled by ISRU technologies that didn't exist at the time of the Apollo Program; This paper present Moonfiber, a project derived from a competition designed by Young Architects Competition (YAC) for the construction of a settlement located in a lunar Lava Tube. This choice is determined by the need to exploit a place with characteristics suitable for human permanence in the long term, achieving a balance between safety and construction complexity. The Moon is a hostile environment, seemingly devoid of blatant resources, subject to the most destructive events in the solar system, such as the constant bombardment of both micrometeorites and radiation, as well as occasional solar storms. The project finds full realization, in its working and living functional divisions, below the lunar surface, while the areas used for ISRU, 3D printing, payload unloading, and energy production operations are located near the entrance of the Lava Tube, to which they connect via a main logistic axis. The main structure, built in the Lava Tube, is made up of a series of inflatable modules held suspended in the center of the gallery by a mesh of composite material fibers obtained through extrusion and winding of regolith fiber. The weaving technique of the supporting structure becomes the turning point regarding the architectural composition of the settlement because it makes everything light and parameterized based on the morphology of the place, which is subject to an automated preliminary scan by robots performing as an avant-garde fleet, extrapolating the optimized topology underlying the definition of the framework of the system. This structure is initially defined by its anchorages to the Lava Tube walls, to which the upper and lower load-bearing fibers are connected, on which rests a mesh, also in fiber, which performs the function of a suspended base for the inflatable modules. The construction technique is based on the processing of the fiber filament. the goal is to obtain the filament from the lunar regolith, adaptable in composition with different quantities and types of yarn, from glass to carbon fiber; the production process of such coils of fiber is described in detail in this paper, along with its installation in a notional Lava Tube.

Keywords: moon
isru
regolith
fibers
lavatube

10:40 AM **4422 - Importance of psychological factors for extraterrestrial base and site planning**

Olga Bannova - University of Houston, Sheryl Bishop - University of Texas Medical Branch, Emeritus, James Wise - retired, Sandra Haeuplik-Meusburger - TU Wien/Space-craft Architektur

Abstract: Our habitats serve two basic functions: To define inside space that serves as shelter and to define outside space that is the rest of the world. Both aspects and their interaction are critical to human functioning and well-being. Thus, the importance of pathways through which we connect the external and internal environments cannot be overestimated, especially in the case of long-term living in isolated, confined and extreme conditions where opportunities for connectivity are limited and challenging. The design of all infrastructure elements, whether a surface or orbital habitat, must comply with unique requirements associated with launch and landing mass and volume constraints, radiation and orbital debris and micrometeoroids protection, availability of resources, resupply delivery, transportation means and power consumption. Although these requirements are continually being scrutinized and improved upon by scientific and engineering communities, there is a notable gap in similar considerations involving the impact of site and infrastructure factors that affect crew performance, health and well-being. This paper presents a short overview of both official and unofficial reports from space crews as well as empirical psychological and human factors research regarding the importance of the ability to visually access the exterior environment, i.e., the world without, in space habitats. The discussion explores the ways in which infrastructure elements and site locations should be equally important considerations in decisions regarding habitat positioning and orientation on the site.

Keywords: human factors
infrastructure
crew performance
site organization
extreme conditions

11:00 AM **6560 - Exploring multi-directional 3D Printing for Enclosures on Earth and Beyond: Sensitivity Analysis of Buildability**

Nusrat Tabassum - The Pennsylvania State University, José Pinto Duarte - The Pennsylvania State University

Abstract: Architecture in space demands innovative solutions to address the challenges of constructing robust, airtight habitats on extraterrestrial surfaces. Additive Manufacturing (AM) has emerged as a promising technology for building habitats on celestial bodies, such as Mars, due to its adaptability and potential for automated construction. For instance, Various teams of researchers from around the globe have found inspiration to participate in NASA competition focused on designing a 3D-printed habitat for Mars. To ensure successful missions, it is essential to develop advanced construction techniques that allow for continuous printing of enclosures without the need for formwork or disjointed segments.

While various techniques for 3D printing houses on Earth have effectively produced numerous building components, certain challenges remain, such as the use of formworks to print roofs or the utilization of separate fabrication methods for roof construction. In the context of space habitats, maintaining airtightness is paramount, necessitating a continuous 3D printing process without interruptions or disjointed sections. To address this crucial requirement, this research delves into approaches to enable the seamless printing of entire structures, including enclosures. The current 3D concrete printing (3DCP) technology, using horizontal or corbeling slicing, restricts the printable overhang angle to a minimum of 60° without formwork. Consequently, formwork-free printing necessitates pointed or conical shapes, limiting design options to tall structures. To

enable shallower structures and greater design flexibility, achieving a lower overhang angle is required.
The aim of this research is to take inspiration from the different types of bricklaying techniques from historical structures and explore the combination of horizontal/corbelling, radial, and inclined slicing techniques for toolpath design in order to 3D print enclosures using a multi-directional printing approach. The objective is to establish rules to decompose enclosed shapes into printable patches and design corresponding toolpaths based on various slicing techniques. This will be achieved by developing an algorithm incorporating the shape grammar rules and numerical modeling software and validating the methodology through the fabrication of a large-scale barrel vault.
Decomposition techniques refer to the process of breaking down complex shapes into smaller, more manageable components for the ease of fabrication. These techniques are often used in architecture to better understand the construction techniques used in historic structures. A shape decomposition method applied to multi-directional 3D printing shows great potential for efficient fabrication in additive manufacturing (AM) while significantly reducing the reliance on formwork for specific geometries. This technique could be seen as the initial stage of transforming the conventional slicing of 3D models for printing, enabling lower overhang angles to overcome challenges in logistically demanding sites.
By combining different slicing techniques, multi-directional 3D printing becomes even more versatile, allowing the production of intricate geometries without formwork constraints. Notably, the rotation of the printing nozzle at various angles during fabrication gradually reduces the overhang angle, ensuring structural integrity and stability.
The fusion of decomposition techniques with multi-directional 3D printing heralds a significant advancement in AM technology. Streamlining the fabrication process and minimizing formwork reliance open up exciting possibilities for constructing complex structures with precision and efficiency. This approach holds particular promise for demanding environments where logistics present unique obstacles, making it a transformative development in modern architecture on earth and beyond.

Keywords: Space architecture
Extraterrestrial habitats
Additive Manufacturing
3D printing
Multi-directional printing
Enclosed structures
Shape decomposition
Earth and beyond

11:20 AM **8003 - Analysis of the end-to-end integration strategy for development of planetary surface architectures.**

Olga Bannova - University of Houston

Abstract: Built environment for human presence in outer space and on other planets has to provide safe environment that should be able to correct itself when critical elements that support life perform outside their intended parameters. This paper will discuss architectural principles and strategies for space applications, environment-specific design influencing factors, integration of engineering and human factors design solutions in the overall architecture of a habitat, base and/or settlement. The major advantage of the end-to-end integration strategy is the combination of benefits of several technologies and methods and applying them when and where they are the most appropriate. Using lunar environment as an example, with this strategy, a special attention is given to constraints and requirements for constructing on the surface of the moon for a prolonged and sustainable human presence and operations. The paper references selected case studies and potential surface architectures that are categorized by their planned purpose, adaptability to modifications, potential for expansion and evolution, and applicability of "exit" strategies. The paper presents analysis of each aspect of surface architectures based on the evaluation criteria and methodology developed by SICSA faculty and students in relation to recent research studies and grants.

Keywords: surface architecture
human factors
sustainable operations
human space exploration
habitats
bases
settlements

11:40 AM **8639 - Towards Resilient Lunar Architecture: A Literature Review of Earth-based Repair Frameworks for Use in Lunar Regolith Construction**

Monika Stankiewicz - University of Adelaide, Amit Srivastava - University of Adelaide

Abstract: With the ambitious vision for long duration lunar habitation on the horizon, the importance of adaptable and resilient architecture to support this vision is coming to the forefront. The lunar environment poses significant challenges to construction and repair through conditions such as extreme thermal cycling and micro-meteorites. These pose a threat to the structural integrity of habitats through damage incurred from hyper-velocity impacts and thermal cycling necessitating the use of design for repair frameworks to lower the risk of critical mission failures. The implementation of design for repairability frameworks at early design stages can reduce the complexity of repair activities, minimizing the resources required. However, as the use of repair-based design frameworks in architecture has yet to be widely adopted, this literature review encompasses methodologies present in areas such as industrial design and civil engineering. In this work we discuss their approaches to design for repair and begin to examine the interdisciplinary applicability of the design features for regolith-based architecture. As humanity's vision for the Moon steadily transitions from aspiration to reality, this literature review shall act as a catalyst for an interdisciplinary approach to design for repair in lunar regolith architecture.

Keywords: lunar architecture
lunar design
repair
repair frameworks
design for repair
ISRU

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Wednesday April 17, 2024: Morning Session

Session Title: Student Paper Finalists I
Session Co-chairs: Robert K. Goldberg, Ph.D., F. ASCE (NASA Glenn Research Center, Cleveland, OH) and Krzysztof Skonieczny, Ph.D. (Concordia University, Montreal, Canada)
Room 115

10:20 AM **3304 - *A new launch pad failure mode: Analysis of fine particles from the launch of the first Starship orbital test flight***

Brandon Dotson - University of Central Florida, Philip Metzger - UCF, Jason Hafner - Rice University, Department of Physics and Astronomy, 6100 Main St, Houston, TX 77005, Autumn Shackelford - University of Central Florida, Kyra Birkenfeld - Rice University, Department of Physics and Astronomy, 6100 Main St, Houston, TX 77005, Daniel Britt - University of Central Florida, Kenneth Purvis - Independent Researcher, Bella Vista, AR 72715, Murray Scudder - Independent Researcher, Centerville, MA 02632, C. Scott Johnson - Independent Researcher, Homewood, AL 35209, John Galloway - Independent Researcher, Charlotte, NC 28278, Jay DeShetler - Independent Researcher, Charlotte, NC 28278

Abstract: This study examines the characteristics, composition, and origin of fine particle debris samples collected following the launch of the first Starship orbital test flight, which suggests a new launch pad failure mode previously unknown. Particle shapes, sizes, bulk densities, and VIS/NIR/MIR spectra, of collected fine particle material from Port Isabel, TX, were analyzed and compared to pulverized concrete, Fondag (high temperature concrete), limestone, and sand recovered from the area near the Starship launch pad after this test flight. Raman spectroscopy was also used to determine mineral compositions of each sample. Results suggest that the fine particle material lofted by the Starship launch is consistent with sand derived from the launch site. These results imply that the destruction of the launch pad eroded and lofted material into the air from the underlying sandy, base-layer. From calculations, this lofted material likely remained suspended in the air for minutes following the launch from recirculation, allowing for transport over an extended range. Most of the recovered material was too coarse to be a respiration hazard, as a small mass fraction of the particles (<1%) had diameters of 10 um or less. Video analysis and ballistic models also provide insight into the failure mechanism associated with the launch pad, which was consistent with a high-pressure eruption from the region below the failed launch pad. As one of the vehicles selected for NASA’s Human Landing System (HLS) contract, the results of this study clearly highlight the implications of plume effects and pad designs for future launches from Starbase, TX, as well as for NASA’s Artemis program.

Keywords: Starship
Plume Surface Interactions
Rocket Exhaust Interactions
Plume Effects
Exhaust
Landing Pads

10:40 AM **4265 - D.N.A. - Designing New Abodes on the Moon: Pioneering the First Permanent Lunar Station**

Marta Rossi - Politecnico di Torino, Federica Joe Gardella - Politecnico di Torino, Mariapia Mammino - Politecnico di Torino, Elif Kirmiziyesil - Politecnico di Torino, Ebru Nur Yavuz - Politecnico di Torino, Valentina Sumini - Politecnico di Milano

Abstract: The realization of the first permanent lunar settlement is going to mark a historic moment that will reverberate throughout history and forever reshape the trajectory of humanity, standing as a testament to the boundless potential of human exploration. It represents the realization of our innate curiosity and thirst for knowledge that has always pushed humanity to go beyond its limits. As we embark on this endeavor it becomes abundantly clear that the design of an outpost on the Moon must transcend mere functionality and instead be conceived as an iconic work of art, paying homage to the indomitable spirit of humanity and our unwavering quest for the unknown.

Grounded in these principles, this research is centered around the design of an architecture, drawing inspiration from the most fundamental essence of life itself: human DNA. Within its intricate complexity lie the secrets of our existence and the capacity for extraordinary growth and adaptation. Drawing a parallel with the first human settlements that emerged within caves thousands of years ago, the structure of the settlement leverages the "natural protection" afforded by the lunar surface, embedding itself entirely within a "lava tube" and connecting to the surface via the Lacus Mortis Pit. Symbolically mirroring the intertwined double helix of our genetic code, the architectural form of the station emerges.

The structure comprises distinct and autonomous modules, conceived for incremental development. Leveraging the power of computational design during the initial planning phases as well as in the later stages facilitates the adaptation of the geometries of the two helixes to the cave section and to the specific requirements in terms of internal volume. The modular nature of the project offers numerous advantages. Firstly, it allows for immediate habitation for the first inhabitants, then it enables expansion over time through module replication and horizontal branching along the tunnel.

This research delves into various aspects of space architecture projects, encompassing interior design, material selection, masterplan configuration, and energy supply strategies. By thoroughly exploring these facets, the project aims to create a comprehensive and sustainable strategy.

The modules consist of a rigid metallic core and a multilayer inflatable package. Prefabricated on Earth, they are then carefully packaged for transportation and assembled on-site. When compressed, the modules occupy minimal volume, which can be accommodated within the spacecraft load. Once on-site, the structures are pressurized, expanding in volume and assuming the spiral configuration. In addition to access through the pit, connections to the lunar surface can be established via elevators leading to small surface constructions, potentially housing observatories.

Thus, with the establishment of this pioneering research outpost, the Space Age would truly commence. This would mark an era where the Moon, with its captivating allure and vast possibilities, would guide humanity towards uncharted horizons. It would ignite our unwavering commitment to explore and comprehend the mysteries of the universe, forging a future wherein the Moon becomes a launchpad to even more distant frontiers.

Keywords: Space Architecture
Moon
Lava tubes
Computational design
Inflatable

11:00 AM **799 - Stresses and Deflection of a Lunar Habitat under Extreme Daily Temperature with and without Regolith Cover**

Sachin Tripathi - University of Connecticut, Ramesh B. Malla - University of Connecticut

Abstract: This paper evaluates the thermo-mechanical behavior of a hypothetical monolithic hemispherical dome-shaped lunar structure, assumed to be constructed at the lunar equator using conventional terrestrial concrete and covered with in-situ lunar regolith. A comprehensive thermo-mechanical analysis of the dome structure, both with and without a protective regolith cover, is conducted using the commercial finite element analysis (FEA) tool, ABAQUS. The analysis incorporates various heat sources, including direct solar radiation and lunar albedo, as well as heat sinks such as non-blackbody radiation and habitat albedo. A solar radiation model, considering structural self-shadowing effects, is developed using the numerical computing software package, MATLAB. The analysis shows that the unshielded dome surface (i.e., the model without the protective regolith cover) experiences extreme temperature variations, ranging from 364 K at solar noon to 222 K at night. The temperature range decreases gradually from the external wall surface to the internal wall surface. For the interior contact surface, temperatures range from 277 K to 309 K, resulting in a maximum temperature fluctuation of about 32 K. However, the use of a 20 cm-thick regolith cover significantly reduces diurnal temperature fluctuations to just 2 K (from ~291.5 K to ~293.8 K). The study also involves stress analysis, which reveals that thermal loading is the primary governing factor affecting the design of the structure. Standard terrestrial concrete structures experience both tensile and compressive failures under extreme temperature conditions and diurnal lunar cycles. These findings underscore the need to account for temperature variations in lunar habitat design. The application of a regolith protection cover shows promise, limiting principal stress to 3 MPa and enhancing structural durability, with potential implications for the success of lunar colonization missions.

Keywords: Lunar habitats/structures
Temperature profile
Thermal Induced Responses
Regolith protective layer
Thermodynamic heat diffusion
Solar radiation
Albedo effect
Structural self-shadow effect

11:20 AM **9225 - Micromechanical and microstructural analysis of lunar concrete**

Mohammad Sulaiman Dawood - Clarkson University, Peter J. Collins - The Pennsylvania State University, Aleksandra Radlińska - The Pennsylvania State University, Robert J. Thomas - Clarkson University

Abstract: This study investigates the micromechanical properties of lunar regolith simulant-based geopolymer concrete (lunar concrete). Geopolymers are cement-like materials made by activating aluminosilicate materials—like lunar regolith—with sodium or potassium alkalis—which are present on the lunar surface. Geopolymerization of the lunar regolith using a sodium silicate solution is one of several in-situ resource utilization (ISRU) technologies being examined as a potential method for producing building materials suitable for lunar structures. However, due to the high cost and limited availability of the simulant materials, it is difficult to perform macroscopic investigations. Therefore, we study the composition, microstructure, and in-situ mechanical properties of component phases to discern into how these materials might behave at the structural scale.
In this study, we investigate lunar concrete made by activating the Off Planet Research H2N (OPRH2N) simulant closely resembling highland lunar regolith (70% Archean anorthosite, 30%

basaltic cinder), with a sodium silicate activator solution ($Na_2O + SiO_2 + H_2O$) in a controlled terrestrial environment (1.0 g, 1.0 atm, 23 °C). We vary the solution-to-simulant ratio, silica modulus (ratio of SiO_2 to Na_2O in the activator solution), and the curing temperature according to a central composite experimental design. We measure the compressive strength using miniature cylinder specimens to obtain the best possible macroscopic information about the material's behavior. This is followed by statistical nanoindentation to characterize the micromechanical properties and scanning electron microscopy (SEM) and energy dispersive spectroscopy (EDS) to characterize the composition and morphology of the microstructure.
Statistical analyses were performed to correlate the input parameters with the compressive strength and micromechanical properties of the lunar concrete samples. Although only a few statistically significant trends were observed, further probing through statistical deconvolution of the nanoindentation results revealed four major phases within the microstructure. The hydrated geopolymer paste contained two distinct phases, which were attributed to a softer N-A-S-H gel and a harder C-A-S-H gel. Similarly, two clusters were identified in the unhydrated portion, and these were attributed to a softer plagioclase phase and a harder phase composed of pyroxene and olivine. The micromechanical signatures of these clusters were in good agreement with those reported for similar systems elsewhere in the literature, and the results were also validated by SEM/EDS analysis of the microstructure. Additional analyses are currently underway, which will provide more insight into the optimal mixture parameters for lunar concrete and the resulting properties they can be expected to exhibit at structural scale. By advancing our knowledge of geopolymer-based materials and their behavior, we can advance the development of sustainable and efficient construction techniques for future lunar structures.

Keywords: Geopolymer lunar concrete
ISRU
Micromechanical properties
Microstructure
Compressive strength

11:40 AM **5867 - Thermal and Structural Analysis of Modular Autonomously Assembled Truss Modules for Space and Lunar Surface Applications**

Nicholas Gross - University of Arizona - SpaceTREx, Athip Thirupathi Raj - University of Arizona - SpaceTREx, Jekan Thangavelautham - University of Arizona - SpaceTREx

Abstract: With the recent surge in the development of space technologies and the growing space economy, the need for large space structures is more present than ever. Large space structures facilitate many space activities requiring larger payloads, power, and propulsion systems. These activities can include long-duration space exploration and the construction of facilities on the lunar surface. To enable such large structures, modular truss structures must be created, which can be assembled autonomously. Truss structures have been used in space for many applications, most notably the Integrated Truss Structure (ITS) on the ISS. It creates attachment points for solar arrays and external payload and contains electrical and cooling utility lines. The ITS has allowed the ISS to receive numerous repairs and upgrades, increasing its lifetime. Creating modular truss structures to be autonomously assembled reduces the risk and cost of deployment and enables repairs, upgrades, and future expansion.
This work discusses the development of truss modules that can be autonomously assembled in deep space and lunar environments. Autonomous assembly of the modules can be done using robotic arms that move across the modules on rails. This is analogous to the Mobile Base System (MBS) on the ISS. The truss modules have probe and cone docking adapters that utilize geometry for soft capture and mechanical latches for hard capture. The adapters can lock and unlock using Shape Memory Alloy (SMA) springs which actuate the latches. A combination of the probe and cone adapters will be attached to each truss module, allowing for expansion in all directions. Both

thermal and structural simulations will be performed on the truss modules with simulation software such as ANSYS. Beginning with static structural analysis, the truss modules will be evaluated when assembled in various configurations. Vibrational load analysis will also assess the docking and assembly process between two truss modules. Multiple truss modules and configurations will be analyzed, each with different truss structures and materials. Each configuration will be simulated in both deep space and lunar environments. The computer-based physics simulations will choose the optimal truss module configuration and material. The optimal designs for the deep space and lunar environments will be compared.
The chosen designs will be constructed with the thermal and structural analysis results. These prototypes will be tested in simulated conditions in the laboratory. A robotic arm will be used to simulate the docking and assembly process. The truss configuration, material, and docking adapter placement will be further validated during this testing. The docking adapters' ability to keep the truss modules assembled and resist separation will also be evaluated. We aim to demonstrate a successful docking and assembly scenario between two truss modules. The ANSYS simulations will use the experimental results to identify and establish the ideal truss configuration for deep space and lunar environments. We further discuss optimizing the truss structure and material for a mass budget.

Keywords: in-space assembly
building blocks
robotics
lunar surface

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Wednesday April 17, 2024: Afternoon Session

Session Title: Regolith Simulants II

Session Co-chairs: Christopher Dreyer, Ph.D. (Colorado School of Mines) and William O'Hara (Blue Origin, Denver, CO)

Room 124

01:20 PM **175 - *Lunar Regolith and its Potential for Space Construction and Geotechnical Engineering: A Review***

Hamed Niroumand - Gdansk University of Technology, Lech Balachowski - Gdansk University of Technology, Matthias Sperl - Deutsches Zentrum für Luft- und Raumfahrt (DLR)

Abstract: Regolith consists of mineral fragments, rock chips, and agglutinates. Lunar soil is the fine fraction of regolith. Many activities in space depend on a thorough understanding of lunar regolith. Many researchers have examined the properties of regolith. A few scientists have created regolith stimulants. Existing regolith has many drawbacks for various applications and goals in the development of the Moon, Mars and other terrestrial planets. Most researchers and engineers want to improve techniques for transforming the Moon, Mars and other terrestrial planets for life conditions. One of the most important aspects is the development of buildings that people can live in for a long time. From this perspective, lunar regolith needs to be investigated, enhanced and used for future construction on the Moon and Mars by 3D printing technique, but existing regolith as an untreated material has many disadvantages at this moment. Furthermore, lunar regolith needs to be investigated as a subsurface layer that geotechnical engineers can design shallow or deep foundations or surface improvement on the Moon, Mars, and other terrestrial planets for engineering purposes. Based on this gap, this research focuses on the investigation of existing regolith and stimulants that can create new opportunities for modified regolith in the future.

Keywords: Lunar
Regolith
Maritain
Moon
Space

01:40 PM **651 - Selection of a Lunar highland simulant for the Luna Analogue Facility (ESA, EAC): A fine-particle testbed**

Aliz Zemeny - PhD, Kamini Manick - Mrs

Abstract: The European Space Agency (ESA) is focused on advancing human exploration by turning its attention to the Moon. As part of the preparations for future lunar habitation, the Luna Analogue Facility is currently being constructed at the European Astronaut Centre (EAC) in Cologne, Germany. This facility consists of three components and spans an area of 1000 m2, providing simulated lunar environments. The main sections within the facility are a large area filled

with lunar regolith analogues resembling mare regions and a smaller, individual "Dust Chamber" that replicates highland conditions and contains approximately 8-10 tons of material, specifically simulating the fine-particle portion up to 90µ.
The Dust Chamber serves as a platform for testing various technologies, such as mechanical tools, robotic operations, in-situ resource utilization (ISRU) activities, and astronaut attire, as well as different procedures including rovers and astronaut tasks. To facilitate this, the Vulcan Analogue Sample Facility at Harwell Campus in the UK has been enlisted to select and characterize the highland simulant for the Luna Dust Chamber. As part of the newly established European Centre for Space Applications and Telecommunications (ECSAT), Vulcan focuses on supporting analogue sample research and technology development projects pertaining to space exploration and planetary science applications at a European level. Therefore, Vulcan's role encompasses choosing the optimal highland simulant feedstock option for the Dust Chamber.
The selection process involves exploring the network of European simulant providers, evaluating the availability and logistical aspects of the materials on the market, including loading time and costs. Furthermore, the properties of the simulants are assessed, encompassing factors such as particle size range, distribution, shape, and modal mineralogy, all of which are crucial for the primary geotechnical and geomechanical purposes of the Dust Chamber. These considerations help narrow down the range of potential highland simulants available in Europe. Ultimately, the most suitable simulant candidate will be chosen to enable comprehensive testing of geotechnical and engineering-related activities within the Dust Chamber, contributing to the accumulation of vital knowledge before humans return to the surface of the Moon.

Keywords: simulant
Lunar Highland
testbed

02:00 PM **3610 - Densification Kinetics of Synthetic Lunar Regolith Using Optical Dilatometry**

Joseph Naikeng Wang - Department of Materials and Engineering, Texas A&M University, Jonathan Lapeyre - Zachry Department of Civil & Environmental Engineering, Texas A&M University, Jeffrey Bullard - Zachry Department of Civil & Environmental Engineering and Materials Science & Engineering, Texas A&M University

Abstract: The kinetics of conventional sintering of two lunar regolith simulants are reported and discussed. Dry-pressed specimens of commercially available Highlands and Mare simulant were heated at 80 °C min-1 to a final isothermal hold for ten hours. The volumetric strain rates and densification rates were calculated based on different sintering temperatures. The Highlands simulant densified more than the Mare at similar temperatures, reaching final densities near 90 % of the theoretical density at 1428 K. The apparent activation enthalpy for densification was measured as 456 kJ mol-1 and 419 kJ mol-1 for the Highlands and Mare simulant, respectively, independent of temperature and sintered density within the measurement uncertainty. These values are consistent with self-diffusion of silicon within anorthite feldspars, the primary component of Highlands regolith and a significant component of Mare regolith.

Keywords: Lunar Simulant
Isothermal sintering
Activation energy

02:20 PM **3948 - LHS-2 and LSP-2: Expanding Exolith Lab's Lunar Regolith Simulants to Particle Sizes >1mm**

Parks Easter - The Exolith Lab, Konrad Krol - The Exolith Lab, Isabel Wilburn - The Exolith Lab, Jared Long-Fox - The University of Central Florida-Department of Physics, Dan Britt - The

University of Central Florida-Department of Physics, Julie Brisset - The University of Central Florida-Florida Space Institute

Abstract: The development of technology for use on the Moon requires accurate lunar surface analogs, also known as lunar regolith simulants. The Exolith Lab produces multiple mineralogically accurate lunar regolith simulants: Lunar Highlands Simulant (LHS-1), Lunar Mare Simulant (LMS-1), Lunar Highlands Dust (LHS-1D), Lunar Mare Dust (LMS-1D), and Lunar Highlands Agglutinate Simulant (LHS-1-25A). These simulants are designed to match the particle size distribution and mineralogical composition of the Apollo lunar samples from both the lunar mare and lunar highlands regions of the Moon.

NASA's Artemis missions are planning to land on the lunar south pole within the next few years, and new lunar regolith simulants are needed to match the mineralogy and particle size distribution of this region. The Exolith Lab has developed two new lunar regolith simulants: a revised Lunar Highlands Simulant "LHS-2" and a Lunar South Pole Simulant "LSP-2". Both of these simulants expand the particle size distribution from a maximum of 1 mm to a maximum of 2 mm, with options to include larger sizes depending on customer needs. The mineralogy of LHS-2 matches that of the Exolith Lab's LHS-1 simulant, while the LSP-2 simulant consists of a more anorthosite dominant composition.

Exolith Lab's Lunar South Pole Simulant (LSP-2) will consist of 90% anorthosite and 10% glass rich basalt with a particle size distribution matching that of returned Lunar Highlands samples, ranging from .01 micron to 2 millimeters [Fruland, 1982]. This mineralogy has been selected as the lunar south pole is estimated to have upwards of 90% anorthosite in composition [Lemelin, 2022]. Mineralogical composition is an essential factor for many lunar applications such as molten regolith electrolysis, plant growth, and lunar infrastructure development.

LHS-2 expands the particle size distribution of the simulant while maintaining the mineralogical composition of LHS-1 that has been utilized in government, industry, and academia. In addition to LHS-2, a bulk version of the simulant titled LHS-2E will exist within the Exolith Lab's 100 m2 regolith bin. More than 140 metric tons of LHS-2E are being produced to fill the regolith bin and provide a testing environment for lunar rovers and other lunar equipment.

Geotechnical characteristics of both of these simulants that will be presented include but are not limited to: particle size distribution, mineralogical composition, bulk density, void ratio, porosity, and angle of repose. With the creation and characterization of these upgraded lunar regolith simulants, we hope to provide a more accurate testing material for scientific and engineering applications on the lunar surface.

Keywords: Lunar Regolith Simulants
Geotechnical Engineering
Civil Engineering
Lunar Regolith
Exolith Lab

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Wednesday April 17, 2024: Afternoon Session

Session Title: Planetary Drilling and Mining
Session Co-chairs: Brian Glass (NASA Ames Research Center, Mountain View CA) and Kris Zacny (Honeybee Robotics, Altadena, CA)
Room 114

01:20 PM **4340 - *Unoccupied Aerial System Coring Drill Sampler Development for Applications on Earth and Other Planetary Bodies***

Colin Chen - Honeybee Robotics, Kathryn Bywaters - Honeybee Robotics, Kris Zacny - Honeybee Robotics, Nicklaus Traeden - Honeybee Robotics, Christopher Hamilton - Lunar and Planetary Laboratory, University of Arizona

Abstract: Unoccupied aerial vehicle technology on Earth has become increasingly prevalent and accessible, and missions to Mars and Titan with Ingenuity and Dragonfly have demonstrated or depend upon unoccupied aerial flight on other planetary bodies. Given the advantages provided by UAS systems for Earth and other planetary bodies within our solar system, quicker and broadened access to traditionally difficult to reach terrain have now become more feasible. To increase UAS geotechnical capabilities and demonstrate UAS-based drilling, we developed a drill sampling UAS platform. The drilling platform is comprised of a lightweight rotary percussive coring drill, mounted to a compliant mount to allow for sampling in varied and uneven terrain. This paper discusses the design and real-world applications of this UAS-drill sampling system.

Keywords: Unoccupied aerial systems
Drilling sample acquistion
UAS
Rock coring
Powder cuttings
Planetary analogs

01:40 PM **192 - Sublimation of water vapor from icy lunar drill cuttings**

Philip Metzger - UCF

Abstract: Detailed modeling has been accomplished to predict the release of water vapor from icy lunar drill cuttings in vacuum. The equations show that heat transfer through a sand pile over 10 minutes time will be significant and will greatly affect the release rate of water. At the relevant temperatures, vapor in the soil reaches thermal equilibrium in less than 1 microsecond at less than 1 Pa of pressure. The pressure gradients in this equilibrium are so tiny that effectively no diffusion occurs from the bulk of the sand pile. Therefore, no sublimation occurs in the bulk of the pile. Instead, diffusion occurs only in a 200 micron deep skin on the outside of the sand pile, and so sublimation of ice is also limited to that thin skin. The rate of sublimation and diffusion from that skin will wane over time as latent heat of sublimation cools the skin. This can be mitigated if the sand pile is in direct sunlight to continuously warm it. The sublimation rate is extremely sensitive to temperature so if the uncertainty in temperature is more than a couple of degrees then it may be impossible to correlate the outgoing flux to a concentration of ice in the soil by better than an order of magnitude. However, integrated modeling can predict the entire curve of the vapor flux as it cools or warms, so this added information helps constrain the ice content despite temperature uncertainties.

Keywords: Lunar ice
Regolith physics
Lunar drill
Lunar prospecting

02:00 PM **7667 - RedWater: Water Mining System for Mars**

Joey Palmowski - Honeybee Robotics, Kris Zacny - Honeybee Robotics, Bolek Mellerowicz - Honeybee Robotics, Bernice Yen - Honeybee Robotics, Jack Schultz - Honeybee Robotics, Kathryn Bywaters - Honeybee Robotics

Abstract: Water ice deposits on Mars present a valuable resource for both propellant manufacturing and human habitation for future missions. Mapping efforts have identified buried ice in the mid latitudes of Mars, ranging from ground ice to debris-covered glaciers. This study focuses on the in-situ resource utilization (ISRU) potential of collecting water in these regions. Under NASA funding, Honeybee Robotics has developed the RedWater system, a TRL6 technology for accessing, melting, and extracting water from the subsurface ice deposits. RedWater combines the use of coiled tube drilling and the Rodriguez well method, proven terrestrial technologies for subsurface access and water extraction. This paper reports the results of the completed end-to-end testing of the RedWater system in simulated Mars conditions, including drilling with pneumatic cuttings clearing, well melting, and water extraction. The performance of the system was evaluated at -60°C ice temperature and Mars ambient pressure, providing insights for future system design and the development of integrated solutions for future mission architectures that will heavily rely on ISRU. This study contributes to the ongoing efforts of advancing those ISRU capabilities, and more specifically, water mining processes on Mars.

Keywords: Mars
Water Mining
Extraction
Coiled Tubing
RedWater System
ISRU

02:20 PM **5388 - RocketM – A Propulsive Excavation System for the Moon and Mars**

Jon Slavik - Astrobotic, Travis Vazansky - Astrobotic, Connor Luken - Astrobotic

Abstract: NASA's return to the Moon with the Artemis Program is expected to stimulate a cislunar economy focused around in-situ resource utilization (ISRU) activities. Lunar regolith and subsurface water ice are two key resources within this ecosystem, and lunar explorers will need systems to excavate and transport these materials across the surface of the Moon. Traditional excavation methods use implements which are susceptible to deterioration, such as scoops, drills, and other mechanical components. The risk of tool deterioration is exacerbated by the properties of lunar regolith, which is very abrasive. To overcome this problem, Astrobotic is developing the RocketM system (Resource Ore Concentrator using Kinetic Energy Targeted Mining), which uses a controlled rocket plume to rapidly excavate material without the need for mechanical digging implements.

The RocketM system is a mobile platform consisting of several key subsystems. The rocket excavator is a small 100-lbf engine positioned approximately 8’’ off the surface. It fires a plume down into the regolith, which excavates a roughly 8,000 cm3 crater and ejects material upwards. The rocket is mounted within a pressure-sealed collection dome to enclose the ejected material. The perimeter of the dome is pressed down into the regolith surface, creating a volume where pressure can be held. An extraction subsystem then removes granular material and ice from the dome and passes it to the beneficiation subsystem, where the two material types are separated. Finally, all subsystems are mounted on a robotic platform that moves the RocketM system to a desired location. The mobile platform is designed to traverse rugged lunar terrain to extract materials from multiple sites and position the system in a wide variety of mining locations.

Astrobotic has developed RocketM to TRL 4 through an SBIR program, which included testing of the rocket engine and dome subsystems on a live rocket test stand. These tests used various types of material that could be found on the lunar surface, including different types of icy regolith as well as dry regolith. These tests demonstrated that the system could successfully excavate a crater using a continuous 2-second rocket firing or successive 0.5-second bursts. Excavated material was collected and weighed after each test fire, and analysis showed that RocketM can excavate 3.9 times more ice than propellant expended in the excavation process. Conceptually, a portion of the extracted ice could also be processed to replenish hydrogen and oxygen propellants for the RocketM system.

Future work will mature other RocketM subsystems and advance towards an end-to-end functional platform that can be deployed to the Moon on a CLPS-class lander, such as Astrobotic’s Griffin vehicle. It will support NASA’s concept of operations for an ISRU water processing plant by delivering 15,000 kg of water over the course of 225 days of operations. It can also be easily adapted to conditions on Mars to support similar ISRU operations there.

Keywords: Mining
Excavation
In-situ resource utilization
ISRU
Rocket

02:40 PM **4010 - The Effect of Bending Vibration Modes on Penetration of Bio-Inspired Drilling Tool in Granular Materials: An Experimental Study**

Mahdi Alaei Varnosfaderani - University of Manitoba, Pooneh Maghoul - Polytechnique Montreal, Nan Wu - University of Manitoba

Abstract: Conventional heavy soil drilling tools are impractical for lunar subsurface exploration due to payload limitations. To overcome this, vibration can be used to reduce the soil penetration resistance and develop a more compact drilling tool for remote subsurface investigations. Therefore, this study aims to investigate the effects of bending vibrations to facilitate probe penetration into granular materials. We attached piezo patches to the probe and conducted experimental modal analyses to determine resonance frequencies. The probe was then inserted into different granular materials, with and without lateral vibrations and corresponding vertical forces were measured. Our test results demonstrate that bending vibration modes significantly reduce the vertical force required for probe insertion into soil samples.

Keywords: Soil drilling
regolith
Vibration
Piezoelectric
Bending Modes

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Wednesday April 17, 2024: Afternoon Session

Session Title: Advanced and Alternative Cementitious Materials
Session Co-chairs: Chris Farraro, Ph.D. (University of Florida, Gainesville, FL) and Hongyu "Nick" Zhou, Ph.D. (University of Tennessee, Knoxville, TN)
Room 126

01:20 PM

5668 - *On the Development of Sulfur Concrete as an ISRU-Based Construction Material for Lunar Infrastructure Applications*

Ilerioluwa Giwa - Louisiana State University, Mary Dempsey - Louisiana State University, Joseph Lamendola - Louisiana State University, Ali Kazemian - Louisiana State University, Michael Fiske - Jacobs Space Exploration Group

Abstract: As mankind gets closer to a long-term, sustainable presence on the Moon, it is imperative to develop technologies that maximize the use of In-Situ Resource Utilization (ISRU)-based materials and processes. Extrusion-based Construction 3D Printing (C3DP) is such a process and offers a large-scale automated construction technique that can be leveraged for planetary construction. Because water-based concretes are unstable during curing in the vacuum of the lunar surface, this paper reports on the use of sulfur as a binder for lunar regolith to make an extrudable lunar concrete. Sulfur concrete is an alternative waterless construction material due to the availability of its ingredients on the planetary surfaces. Previous works suggest that the use of sulfur concrete is problematic due to the low melting point and relatively high sublimation rate in the lunar equatorial environment. However, as early Artemis missions are focused on regions near the lunar South Pole, this effort focuses on use of this material in polar applications (and associated thermal environment). In addition, this study investigates the behavior of sulfur-regolith concrete as a candidate material for planetary C3DP, by studying the printability and performance of 3D printed samples made with a lunar highlands regolith simulant. Based on these, and previous experimental findings, the printability and mechanical performance of sulfur concrete can be impacted by process parameters such as the printing temperature and interlayer time gap.

Keywords: Lunar Infrastructure
Lunar Construction
Sulfur Concrete

01:40 PM

7067 - 3D printed geopolymer concrete made of lunar regolith simulant for use in space construction

Ehsan Mohseni - University of Tennessee Knoxville, Peyman Zandifaez - University of Tennessee Knoxville, Hongyu Zhou - University of Tennessee Knoxville

Abstract: One of the promising options for construction on the Moon surface is concrete using local resources instead of transportation of materials. Lunar regolith simulant which is mostly made of silicon and aluminum oxides is the only option in order to constructing concrete materials

with local material. In addition, geopolymer concrete seems to be a reasonable solution for in-space constructions not only due to the benefits it provides in terms of mechanical and durability properties, but also its environmental advantages. On the other hand, 3D printing technology is a constructive solution for the in-space construction. Although 3D printing of concrete has not yet been ready to replace conventional site cast or prefabricated construction, the many advantages of this technology has made it uniquely qualified for immediate applications where conventional reinforced concrete would not be feasible. Possibility of automation and faster manufacturing have made this technology to be one of the best options for the in-space construction. In this study, 3D printed geopolymer concrete made with lunar regolith simulants is investigated. Mechanical and durability properties will be discussed via compressive strength, resistance against high temperatures and drying shrinkage.

Keywords: 3D printing
Geopolymer concrete
Lunar regolith simulant
In-space construction

02:00 PM **2618 - Effects of lunar surface temperature swing on the mechanical properties of 3D printed concrete**

Peyman Zandifaez - University of Tennessee Knoxville, Reese Sorgenfrei - University of Tennessee Knoxville, Ehsan Mohseni - University of Tennessee Knoxville, Hongyu Zhou - University of Tennessee Knoxville

Abstract: Space construction missions necessitate the on-site printing of structures, ensuring both high durability and mechanical performance. However, the harsh environmental conditions present in accessible space environments such as Mars and the Moon pose significant challenges to the mechanical and durability properties of 3D printable cementitious composites. Therefore, in-depth investigations of the behavior of cementitious composites under such extreme environmental conditions become crucial in overcoming these potential obstacles. The objective of this study is to investigates the effects of the extreme environmental conditions, in particular temperature fluctuations, on 3D printed concrete structures. To achieve this goal, CSA cement and lunar regolith simulants are used for concrete 3D printing. The mechanical samples are prepared and exposed temperature swings ranging from -80℃ to 200 ℃. The compression strength, elastic modulus, flexural strength, and durability of the samples are examined after exposure to temperature cycling. Furthermore, this study investigates the impacts of extreme temperature fluctuations on the microstructure of 3D cementitious composites using SEM imaging. The results show that the all mechanical indices and durability of 3D printed samples are negatively impacted throughout the temperature swings. The obtained results are confirmed by SEM imaging, which reveals the detrimental effects of temperature fluctuations on the microstructure of samples by adversely impacting both the quantity and width of the cracks, thereby increasing their permeability. The findings of the study provide valuable insights into the behavior of the 3D printed elements in space environments, contributing to the unexplored horizons of advanced construction approaches and habitation beyond terrestrial applications.

Keywords: Concrete 3D Printing
Temperature Swing
Extreme Environment
Mechanical Properties

02:20 PM **4282 - Engineered Ultra-flexible Construction Composites using Lunar and Martian Regolith Simulants for Extraterrestrial Construction on the Moon and Mars: Bendable LunarCrete and MartianCrete**

Qingxu Jin - Michigan State University, Matias Leon-Miquel - Michigan State University, Nathan Denning - Michigan State University

Abstract: One of NASA's key strategic plans and priorities is to explore a sustained presence and operation on the Moon and Mars through safe and reliable infrastructure on their surfaces. The agency has invested in advanced manufacturing to enable space exploration – such as the Moon to Mars Planetary Autonomous Construction Technologies (MMPACT) project and 3D Printed Habitat Challenge. To achieve this goal, we must identify and utilize the available resources on the Moon and Mars, also known as in situ resource utilization (ISRU), to construct space-based infrastructure. Previous research has demonstrated that some candidates of lunar and Martian regolith simulants could be the precursor for producing construction materials on the moon and Mars. However, the harsh environment in space presents a huge challenge to maintaining the long-term performance of the space infrastructure.
This presentation will show engineered ultra-flexible and -ductile construction composites using lunar and Martian regolith simulants: bendable LunarCrete and MartianCrete. The composites exhibit unusual ductile behavior like malleable metal and 200-300 times more resistance to cracking than conventional concrete. The bendability has been characterized using four-point bending and direct tension tests. The ultra-high ductility could help eliminate the use of steel reinforcement, which could be advantageous for lunar and Martian construction to eliminate the need to produce metals. To correlate the behavior with different simulants, we have also carried out experimental studies to characterize the physical and chemical properties of these stimulants, including surface features, particle size analysis, hydraulic reactivity and pozzolanic reactivity, chemical composition, rheological properties, and compressive and tensile strengths when mixed with ordinary Portland cement. Two lunar simulants (LHS-1 and LMS-1) and four Martian simulants (JEZ-1, MGS-1, MGS-1C, and MGS-1S) have been selected for the study.
To further improve the mechanical properties of bendable LunarCrete and MartianCrete using lunar and Martian regolith simulants, we have performed several methods, which can be easily executed in space, to enhance the simulants reactivity: 1) mechanical treatment to reduce the particle size of the simulants and increase the materials' specific surface area and 2) thermal treatment on the simulants to alter the materials' mineralogical properties. The reactivity, particle size, and compressive strength of all simulants before and after the aforementioned treatments have been characterized and compared. For example, JEZ-1 simulants showed no hydraulic reactivity but with an indication of good pozzolanic reactivity. After being thermally treated at 600 C, the pozzolanic reactivity of JEZ-1 experienced a slight decrease; however, there was an increase in hydraulic reactivity. In this presentation, we will also present insights into how these treatments affect the mechanical property and reactivity of the composites using lunar and Martian regolith simulants.

Keywords: Ultra-flexible materials
Lunar and Martian Regolith Simulants
Novel materials and structures
Materials for extraterrestrial environment

02:40 PM **1749 - Unlock CO2 sequestration potential of concrete through a biomolecule-regulated carbonation process**

Xiaodong Wang - The University of Alabama, Monica Amaral - the University of Alabama, Jialai Wang - Thu University of Alabama

Abstract: Concrete with ordinary Portland cement (OPC) as the main binder is the most widely used construction material in the world. On one hand, the production of OPC is highly energy-intensive and responsible for approximately 8% of global CO2 emissions. On the other hand, the massive volume of concrete used in construction each year offers one of the largest sinks for CO2 through a mineral carbonation process. However, existing technologies can only sequestrate very small amount of CO2 due to the inherited limitation of the existing carbonation methods. The major objective of this study is to increase the amount of CO2 sequestrated in concretes by at least one order of magnitude higher than existing technologies and drastically increase the compressive strength of the produced concrete. To this end, a biomolecule regulated carbonation (BioCarb) method is proposed, in which the cement slurry is converted into CO2 absorbent and the formation of the in-situ produced calcium carbonated nano/macro particles is regulated by a biomolecule. Testing results suggest that this method can store at least 15lb-CO2 in one cubic yard of concrete, and enhance the compressive strength of the concrete over 30%, drastically reduce the CO2 emission of the produced concrete.

Keywords: Carbon sequestration
low-carbon concrete
nanoparticles

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April 15 - 18, 2024; Greater Miami, FL

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Moss School of Construction, Infrastructure and Sustainability

Wednesday April 17, 2024: Afternoon Session

Session Title: Tensegrity – Concepts and Applications in Challenging Environments

Session Co-chairs: Landolf Rhode-Barbarigos, Ph.D. (University of Miami, Coral Gables, FL) and Sushrut Vaidya, Ph.D. (University of Connecticut, Storrs, CT)

Room 128

01:20 PM **5046 - *Tensegrity - an underexploited structural concept for terrestrial and space applications***

Landolf Rhode-Barbarigos - Dept. of Civil and Architectural Engineering, College of Engineering, University of Miami

Abstract: Tensegrity is a structural concept originating from art. It represents structures composed of axially loaded members whose overall integrity, stability and performance including damage tolerance are defined by the system's force equilibrium under prestress. Tensegrity structures, if properly designed, can be extremely efficient structures; researchers have shown that the minimal mass solutions under external loads correspond topologically to different tensegrity systems. Besides having a great mass-to-strength ratio, tensegrity systems are also collapsible in the absence of prestress and in some cases deployable. The concept has thus received significant interest among scientists and engineers. However, there are only few examples of tensegrity structures considered for terrestrial and space applications. Key challenges include a lack of control over their structural form and mechanical response along with a sometimes-complex assembly and prestressing phase. Most studies have thus been exploring existing tensegrity configurations rather than defining tensegrity systems based on the project or mission requirements and needs. This presentation will discuss the use of tensegrity structures in terrestrial and space applications - from rapidly erected structures to smart transformable systems - along with their related challenges. Cellular morphogenesis, a novel computational method for the generative design of tensegrity structures, will be reviewed as a method that combines form finding with topology identification and thus has the potential to open the door to the development of a whole new realm of tensegrity applications.

Keywords: Tensegrity
Terrestrial applications
Space applications
Form finding
Topology
Construction
Deployable structures
Smart structures

01:40 PM **530 - The optimal dynamical model for 3D tensegrity morphing airfoils**

Muhao Chen - Department of Aerospace Engineering, Texas A&M University, College Station, TX 77840, Yuling Shen - School of Future Science and Engineering, Soochow University, Suzhou, *Jiangsu, 215222, Robert E. Skelton - Department of Aerospace Engineering, Texas A&M University, College Station, TX 77840*

Abstract: This research challenges the assumption that enhancing physical detail within models invariably increases precision. While this holds in physics, modeling is not exclusive to this discipline. The comprehension of our complex world is hampered by incomplete physical laws, imperfect physical law models, and errors in model computations. These errors can manifest even with refined physics-based models, making our simulations less precise. Successful modeling transcends physics, necessitating the integration of signal-processing components to construct robust models for engineering systems.
We propose a model reduction method to establish the 'optimal simulation model' – the one that minimizes errors arising from both modeling and computation in a finite word-length computing environment. By integrating computational errors into system dynamics, the output error of the simulated system can be minimized. The algorithm aids in pinpointing the ideal model size where total simulation error is minimized. We study the application of this approach on 3D tensegrity morphing airfoils, structures with potential in aerospace engineering, to demonstrate its efficiency. The findings suggest that we can deliberately induce dynamics error to yield a smaller total simulation error. The algorithm is applicable for determining the optimal model size and minimum necessary computing resources for other similar morphing structures as well.

Keywords: tensegrity
model reduction
morphing airfoils
high-dimensional system
finite word-length computing

02:00 PM **2996 - Design of multi-stable tensegrity lattices for energy dissipating and shape-morphing structures**

Ranganathan Parthasarathy - Assistant Professor, Tennessee State University, Srinivasan Sivakumar - Professor of Applied Mechanics, Anil Misra - Glenn L. Parker-James L. Tyson Professor of Engineering Mechanics, Hriday Roy - High School Senior at Brentwood High School, Paul Resch - Manager of Additive Manufacturing, Kehinde Omotayo - Graduate student, Tennessee State University, Andrew Mikhaeil - Undergraduate Student, Department of Civil and Architectural Engineering, Mohammad Amin Hodaei - Graduate student, Tennessee State University, Lin Li - Dean of Engineering, Catherin Armwood-Gordon - Department Chair of Civil and Architectural Engineering, Associate Dean of Research, Roger Painter - Professor of Civil and Architectural Engineering, Youngjae Choi - Assistant Professor of Structural Engineering, Deo Chimba - Professor of Civil and Architectural Engineering

Abstract: Tensegrity structures include pre-stressed trusses where compression members float without contacting each other in a network of tension. They can be designed to have multiple stable configurations, which can be used as a mechanism for energy dissipation without damage at the material level, as well as for shape morphing. Release of stored potential energy through internal mechanisms facilitates energy dissipation. Loading conditions that initiate switching between stable configurations can be tuned by varying the pre-stress and undeformed member lengths. However, identifying or designing tensegrity geometries which exhibit multistability is a challenging problem and current research area. We have discovered that the simplex tensegrity, which is the simplest 3-dimensional tensegrity truss, shows a structural phase transition under compression, to a geometrically equivalent, but spatially rotated configuration. When the structure is compressed to a critical state corresponding to a local maximum in its potential energy landscape, further deformation is accommodated by internal rotation of one of the struts, rather than potential energy increase in the bands. At the end of the transition, the structure reaches a

new configuration which is a twin of the undeformed one. The transformation is reversible and can be used for damage-free energy dissipation as well as for shape morphing applications.
The phase transition is demonstrated using a proof-of-concept model built using wood dowels for the compression members and elastomeric bands for the tension members. A simulation model of the phase transition under compressive loading matched the experimental results for critical deformation at initiation of the transition, as well as the corresponding vertical load. Due to large nodal displacements and internal rotations of compression members which induce high geometrical non-linearity into the problem, the determination of the equilibrium configuration, i.e. form finding, as well as the structural analysis of the phase transition were both conducted using potential energy minimization in a constrained optimization routine, rather than using a force-based approach.
To achieve energy dissipation and shape morphing as applicable to arbitrary structural geometries, the phase transition must be translated to a lattice scale. However, tensegrity unit cells cannot be scaled up from unit cells in the manner of traditional non-prestressed lattices since the state of pre-stress and corresponding geometry at lattice scale is altered with each additional module. As a result, the unit cell deformation is not representative of a lattice assembly even for linear elasticity. A modified lattice-to-macro deformation bridging relationship is being designed borrowing concepts from the virtual work method in a granular micromechanics framework(dell'Isola & Misra, 2023) and implementing it into a machine learning algorithm. In particular, the bridging scheme is being designed entirely in an energy-based framework due to high geometrical non-linearity. A scaling law for the scheme that varies with module number and arrangement is being explored.
A potential application of the observed phenomenon is to greatly reduce the energy required to switch between two desired shapes in active morphing structures such as robotic wings or opening bridges as applied to space exploration vehicles. The transition can also be exploited to design impact-absorbing structures based on lattice materials formed by combination of individual simplex modules. The results of this research will also potentially inform the design of architected metamaterials for acoustic devices. The demonstrated phase transition can also be used to design crystal-twinning inspired lattice metamaterials.
dell'Isola, F., & Misra, A. (2023). Principle of Virtual Work as Foundational Framework for Metamaterial Discovery and Rational Design. Comptes Rendus. Mécanique, 351(S3), 1–25.

Keywords: tensegrity
virtual work
simplex
granular micromechanics

02:20 PM **4887 - Sensor Fault Detection Approach to Tensegrity Structures Using Markov Parameters**

Yuling Shen - School of Future Science and Engineering, Soochow University, Muhao Chen - Department of Aerospace Engineering, Texas A&M University, Ed Habtour - Department of Aeronautics & Astronautics, University of Washington, Seattle, WA, USA, Robert Skelton - Department of Aerospace Engineering, Texas A&M University

Abstract: This paper introduces a sensor fault detection method based on output error covariance and demonstrates its efficacy on tensegrity structures. An approximation model of the fault system is developed first using input and output signals. Subsequently, this fault system is compared with a reference system, and their output covariance is analyzed using the Markov parameters of both systems. In addition, an algorithm is presented to identify the fault sensor channels from the output error covariance. An examination of a tensegrity double prism tower, assuming fault sensors producing zero-mean Gaussian white noise, is conducted. The result validates the effectiveness of this approach in pinpointing the malfunctioning sensor channels. This proposed approach is adaptable to other structural fault sensor applications.

Keywords: Tensegrity Structures
Sensor Fault Detection
Markov Parameters

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Wednesday April 17, 2024: Afternoon Session

<u>Session Title:</u> Engineering & Construction of Lunar and Martian Infrastructure Utilizing In-Situ Materials
<u>Session Co-chairs:</u> Melodie Yashar (ICON Technology Inc. Austin, TX) and Tai Sik Lee, Ph.D. (Korea Federation of Science & Technology Societies(KOFST) and Hanyang University, Ansan, Korea)
Room 117

01:20 PM **2686 - *Application of Regolith Polymer Composite Fused Granular Fabrication Construction in Simulated Lunar Conditions***

Nathan Gelino - NASA, Kennedy Space Center, Evan Bell - NASA, Kennedy Space Center, David Malott - AI SpaceFactory, Stephen Pfund - LERA Consulting Structural Engineers, Matt Nugent - Engineering Research and Consulting LLC, Marco Gudino - NASA Kennedy Space Center

<u>Abstract:</u> NASA's Artemis program has the goal of creating a sustained lunar presence to provide unprecedented opportunities for scientific discovery and to ensure industry's access to the unlimited resources and commercial potential in space. To achieve this goal, NASA must incrementally develop and expand its capabilities beyond the short lunar stays of the Apollo program to a robust continued presence with infrastructure and equipment to reduce mission risk. Kennedy Space Center's Granular Mechanics and Regolith Operations laboratory (a.k.a. Swamp Works) has partnered with SpaceFactory and LERA Consulting Structural Engineers to develop the architectural and structural design of a robotically constructable unpressurized shelter. The shelter, called Lunar Infrastructure Asset (LINA), is designed to protect astronauts and surface assets from radiation, meteoroid impact, thermal gradients, and to withstand moonquakes. A Fused Granular Fabrication (FGF) construction process using regolith polymer composites was developed. The construction system and associated print parameters are discussed along with the environmental simulation equipment and a summary of test conditions. Test samples were printed in dirty thermal vacuum conditions (~10-3 torr, ~-200 °C,) and subscale versions of LINA were printed on a regolith simulant substrate in vacuum (~10-4 torr). Full scale LINA design optimization, simulation, and construction concept of operations are discussed.

<u>Keywords:</u> lunar infrastructure
radiation shelter
nasa
lunar construction
kennedy space center
swamp works
swampworks
additive construction
regolith polymer composite
FDM vacuum
3d print thermal vacuum
DTVAC

01:40 PM **7222 - Topological Interlocking Bricks for Habitat Construction in Extraterrestrial Environment**

Maëlle Mathieu - Department of Civil, Geological and Mining Engineering, Polytechnique Montréal, Parisa Haji Abdulrazagh - Matrix Engineering & Trading Ltd, Alexander Jablonski - 3David Florida Laboratory/Canadian Space Agency and Dept. of Mechanical and Aerospace Engineering, Carleton University, Pooneh Maghoul - Department of Civil, Geological and Mining Engineering, Polytechnique Montréal

Abstract: As NASA and other space agencies prepare for a sustained return of humans to the Moon, one key focus area pertains to the challenges of constructing resilient habitats in space. Traditional approaches suggest using robots for single-pass 3D printing of entire habitats, yet this method is constrained by the size limitations of the robots themselves. In this paper, we propose an adaptable and modular approach for human habitat construction based on topological interlocking bricks. These 3D-printed structural elements are designed with specially shaped elements that lock together in such a way to offer enhanced resilience and modularity compared to conventional methods. However, the development of extraterrestrial structures requires a consideration of the extreme environmental conditions, the use of in-situ resources and on-situ fabrication capabilities. We conducted a review of environmental conditions on the Moon to provide useful information regarding structural requirements, available materials, and fabrication methods. We presented various topological interlocking systems and evaluated different assemblies under lunar gravity to recommend an ideal solution for different types of lunar structures.

Keywords: Topological interlocking
Additive manufacturing
In-situ resource
Extra-terrestrial construction

02:00 PM **4097 - Quality Assurance for Construction on the Moon, Mars and Beyond**

Ramiro Besada - Burns & McDonnell

Abstract: Every serious infrastructure project on Earth will have a quality plan developed specifically for it that will cover the engineering, procurement and construction phases. Similarly, infrastructure on the Moon, on Mars or beyond must also have a quality plan developed specifically for each individual project. This presentation will provide an outline of what such a plan should cover.

The construction quality plan of a project establishes the processes needed to guarantee that it will be built in accordance with the drawings, specifications and standards (no codes to comply with on the Moon or Mars, yet!), and the tools and documentation required to confirm that it was built in compliance. The quality plan must cover all the parties involved in the construction of the facility.

Quality aspects of Pre-construction activities are very important but in the interest of time will not be covered in this presentation.

We will cover seven major components of a construction quality plan: the organizational chart, roles and responsibilities; procedures; the inspection and test plan; pre-task planning; document control; receipt and storage; non-conformance.

As part of the plan an organizational chart will be developed illustrating all the functional groups that are involved, together with a description of the roles and responsibilities of each and the communication protocols.

As part of the construction quality plan detailed procedures will be developed that explain every process, and activity that will be performed to build the project, and their requirements.

An inspection and test plan will be included, and it will layout every inspection and test that must be carried out during the construction process of the facilities. It will explain how to determine that each component or sub-system is acceptable before continuing with the installation of the follow on components or sub-system, and the final acceptance and start up of the facility. Further, it will establish the documentation that will be generated during and as a result of the inspections and tests.
The quality plan will specify what pre-task plans must be developed and what pre-task meetings must take place before specific tasks or activities on site can start, to verify that the personnel involved understand the construction or installation process of the task at hand and that all the necessary documentation, materials, tools and equipment are ready and in proper conditions. How to determine compliance with the design and installation requirements will also be discussed.
Document control is another key aspect of the quality plan. It should state how documents are identified, distributed, verified, stored and revised, the people involved in each of these steps, and the tools (e.g. software) that will be employed.
Unloading, unpacking, storage and preservation of materials, tools and equipment on the lunar, martian or extraterrestrial surface is also addressed in the quality plan. It will also consider overages and shortages of elements/components/tools/equipment, and how to handle damages. Protocols on how to Handle non-conforming materials, installations or sub-systems will be explained in detail in the quality plan.
In summary the quality plan lays out how to build the project and what to do to confirm that it is built in compliance with the requirements.

Keywords: quality
construction
control
assurance
testing
compliance

02:20 PM **7575 - Sustainable Material in Space Construction Has Equitable Effect on Earth**

Erika Rivera - Florida International University, Mohamed Elzomor - Florida International University

Abstract: As space becomes the next frontier that humankind is moving forward in discovering and colonizing, it is crucial to evaluate the removal of construction resources from this Earth to prepare other places suitable for human exploration and habitation, understanding that the acquiring process of those resources is executed and coordinated in a socially sustainable manner. Currently, the resources on Earth are limited and can only partially provide resources to developing countries that, in their process, are currently reporting shortages and inequitable workforce conditions. Cement, specific electrical components, wood, steel, and paint are all in limited supply, according to the Construction Leadership Council. Many of the resources utilized in the construction industry provided on Earth are sourced by underrepresented and exploited communities that provide low-cost labor for these products to be available. Exploiting marginalized communities such as women, children, minorities, and underrepresented groups is an ongoing social sustainability problem in the construction industry. According to the International Labour Organization, the construction industry has the second-highest number of coerced laborers worldwide. To continue the expansion process in space, the need to construct amenities that can shelter and provide facilities to humankind in space has to be developed with known materials that will need to be provided by these industries and used in space exploration. This study will evaluate the effect space construction can have on the resources of Earth and the effect on the different industries that provide material to the construction sector, determining if social sustainability is an essential factor in the material procurement process. This paper will add to the community of knowledge the understanding of the effect of the exportation and exploitation of materials on Earth to advance the development of construction in space and that the social sustainability of the acquisition process has to be considered.

Keywords: Social Sustainability
Construction
Equity
Material

Wednesday April 17, 2024: Afternoon Session

<u>Session Title:</u> Student Paper Finalists II
<u>Session Co-chairs:</u> Robert K. Goldberg, Ph.D., F. ASCE (NASA Glenn Research Center, Cleveland, OH) and Krzysztof Skonieczny, Ph.D. (Concordia University, Montreal, Canada)
Room 115

01:20 PM **8998 - *Behavior of Stuffed Whipple Shields Subjected to Micrometeoroid and Orbital Debris Impact***

Md Abdur Rakib - The Andy Thomas Centre for Space Resources (ATCSR), The University of Adelaide, SA, 5005, Australia, Scott T Smith - ATCSR and School of Architecture and Civil Engineering, The University of Adelaide, SA, 5005, Australia, T. Tafsirojjaman - ATCSR and School of Architecture and Civil Engineering, The University of Adelaide, SA, 5005, Australia.

<u>Abstract:</u> In order to build permanent off-earth structures, protection against the hypervelocity impact (HVI) of micrometeoroids and orbital debris (MMOD) is required. Shielding systems comprising single or multiple walls are currently being used in different parts of the International Space Station (ISS) as well as in spacecraft. Stuffed Whipple shield (SWS), a derivative of the Whipple shield, has been used in some parts of the ISS. However, the behavior of the shield is not entirely understood due to the complex nature of the impact. This paper provides an overview of the response of the SWS to HVI of projectiles. Firstly, the baseline configuration of the shield is briefly introduced. Experimental assessment methods used to evaluate the behavior of the shield are discussed, along with the response of the shield. Design equations for predicting the performance of the shield and sizing it are also presented. Finally, the prediction of the equation is validated with the experimental data available in the literature.

<u>Keywords:</u> MMOD
Shielding system
Design equation
High-velocity impact
ISS
Spacecraft

01:40 PM **6672 - On a Nonlinear, Locally Resonant Metamaterial With Topological Features**

Arun Malla - Virginia Tech, Joshua LeGrande - Virginia Tech, Oumar Barry - Virginia Tech

<u>Abstract:</u> Elements such as local resonators, nonlinear elements, or topological properties have each been demonstrated to add beneficial features to metamaterials. However, few works examine combinations of these elements, and none explore the potential of a metamaterial system with all three. In this paper, we address this gap in the literature by examining a 1-dimensional nonlinear metamaterial with coupled local resonators. Quasiperiodic modulation of selected parameters is utilized to achieve topological features. Both analytical and numerical methods are used to study the proposed nonlinear system, with the method of multiple scales

utilized to solve for the infinite chain response while the method of harmonic balance is used to determine the response of the finite chain. The resulting band structures and mode shapes of both the main cells and resonators are used to study the effects of quasiperiodic parameters, excitation amplitude, and sources of quasiperiodicity on the system behavior. Specifically, the impact of these parameters on topological features such as the topologically trivial bandgap, localized edge states, and other localized modes. In addition to topological effects, the effects of nonlinear springs and local resonators are also confirmed with observation of phenomena such as discrete breathers.

Keywords: Metamaterials
Vibrations
Topological
Quasiperiodic
Nonlinear
Dynamics

02:00 PM **4991 - Effects of printing defects on the mechanical performance of 3D printed concrete structures and retrofitting**

Reese Sorgenfrei - University of Tennessee Knoxville, Ehsan Mohseni - University of Tennessee Knoxville, Hongyu Zhou - University of Tennessee Knoxville, Peyman Zandifaez - University of Tennessee, Knoxville College of Civil and Environmental Engineering

Abstract: Understanding the effect printing defects have on the mechanical performance of concrete 3D printed structures and developing materials to effectively retrofit printed elements will be necessary for infrastructure development on the lunar surface and beyond. Various defect sizes, amounts, and orientations were introduced by placing spherical EPS beads of a known diameter within printed specimens to simulate a wide range of possible printing defects. The effect that the introduced voids had on the mechanical performance was then characterized by testing cube specimens cut from the printed elements in compression. The void orientations resulting in the highest drops in capacities found in the initial round of compression testing were then replicated using a mixture developed by the Marshall Space Flight Center to understand the effects voids have on printed elements containing regolith simulants. The next phase of the project was focused on characterizing the effectiveness of epoxy, polyester, polyurethane, ultra-fine cementitious materials, and sulfur-based materials for retrofitting defected samples. The compressive capacity of cube molded specimens, direct tensile capacity of dog bone specimens, and flexural capacity of flexure specimens were characterized to guide the selection of the most optimal retrofitting materials. The two materials with the highest capacities in the mechanical properties tests were selected to eventually be used to retrofit defected samples and prove their effectiveness.

Keywords: Concrete 3D printing
Defects
Mechanical properties
Retrofitting

02:20 PM **4374 - Bolted flange looseness detection using percussion-induced sound and deep clustering**

Jian Chen - univeristy of houston, Gangbing Song - univeristy of houston

Abstract: Bolted connection is widely used in the pipeline system in many industries. However, in the pipeline system, bolted connection represents a point of vulnerability and is prone to self-loosening due to some factors, such as chemical erosion and mechanical vibration, which might lead to economic losses and environmental pollution. Therefore, it is significant to detect the bolt looseness of the pipeline flanges. In recent years, bolted flange looseness detection through percussion-based method and machine learning/deep learning methods have received much attention due to the advantages of removing the requirement of sensor installation and potential for automation. In these methods, a hammer and smartphone are used to collect the percussion-induced audio signals from the bolted flange under different preload levels. Then the collected audio signals are employed to train and test the detection model (classification task). However, supervised learning requires ground-true labels and balanced training datasets. In the practical engineering, it is hard to collect enough percussion-induced audio signals for each classes to build a balanced training dataset. Particularly, abnormal data is far less than the normal data in the training dataset. Therefore, the research aims to develop a deep clustering algorithm to detect the looseness of the bolted flanges, which is label-free (baseline-free) method to find the outliers. If successful, our approach will be used to find the abnormal bolt of the flange, then the classification model (supervised learning) will be used to further identify the looseness level of this bolt. This deep clustering method will work together with the classification model to fully ensure the effectiveness of the detection of the bolted flange looseness.

Keywords: Bolted flange looseness detection
Deep clustering
Percussion-method
Structure health monitoring
Bolted connection looseness
Percussion-induced audio signal

02:40 PM **2057 - Physics Informed Neural Network for Inverse Estimation in Presence of Sparse Data**

Anthony G. Lore Starleaf - Department of Aerospace Engineering, Embry Riddle Aeronautical university, Siddharth S. Parida - Department of Civil Engineering, Embry Riddle Aeronautical University, Souvik Chakraborty - Department of Applied Mechanics, Indian

Abstract: Accurate and efficient characterization of system parameters are pivotal for design and analysis of both terrestrial and extra terrestrial civil engineering structures. To this end, this research focuses on developing a machine learning framework that fuses physical laws with sparse dynamic data to inversely characterize physical systems. A finite element based physics informed neural network (FE-PINN) algorithm is proposed. It is hypothesized to inversely estimate system parameters from sparse data accurately and efficiently. The algorithm uses governing physics equations posed in their weak form in the loss function used to train the neural network along with the usual data loss term used in traditional neural networks. Effectiveness of the proposed framework is demonstrated numerically, by accurately estimating the elastic modulus of a 5m × 10m soil column using dynamic response obtained from the system. Even though the verification of the framework is numerical and simplistic, but the success provides a sense of optimism to extend this work to more complex geotechnical as well as structural engineering problems.

Keywords: Inverse problem
Physics informed neural networks
Site characterization

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Wednesday April 17, 2024: Late Afternoon Session

Session Title: Space Mining
Session Co-chairs: Robert Mueller (NASA Kennedy Space Center, FL) and Laurent Sibille (Southeastern Universities Research Association, NASA Kennedy Space Center, FL)
Room 114

03:40 PM **2980 - *Discrete Element Modeling of IPEx Bucket Drum-Lunar Regolith Interactions***

Daniel Gaines - Clemson University, Qiushi Chen - Clemson University, Laura Redmond - Clemson University

Abstract: In this work, a discrete element model (DEM) is developed for the IPEx bucket drum-lunar regolith system. Model parameters are calibrated using available BP-1 lunar simulant experimental test data. The calibrated model is then applied to simulate a target IPEx drum-regolith system. Modeling the IPEx drum motion using a force controller has shown that the excavation force and the torque behavior can be modeled with a reasonable amount of accuracy when evaluated against experiment data. The mass accumulation rates from simulations matched reasonably with those from physical experiments. The lunar gravity simulation yielded a lower excavation force and torque on the drum than the earth gravity simulation. This study has laid the groundwork for analyses of other IPEx drum sizes and translational speeds and for the coupling of DEM with advanced control models for more accurate force and torque evaluations.

Keywords: IPEx
Bucket drum
Discrete element modeling
Lunar regolith simulant
Excavation

04:00 PM **9466 - Technical Trade Studies on Various Electrolysis System Architectures for Hydrogen Production from Lunar Water**

David Dickson - Colorado School of Mines, George Sowers - Colorado School of Mines, Gregory Jackson - Colorado School of Mines, Chris Dreyer - Colorado School of Mines

Abstract: Recent discoveries and mapping of resources on the Moon have made the possibility of fuel production in space very real. It is believed that between 1 billion and 10 billion metric tonnes of water ice may be found in and around the lunar PSRs. Efforts are underway now to develop technology to reliably utilize lunar water in a manner that employs solid systems engineering practices to settle, explore, and industrialize the Moon as part of the greater project of exploring the Solar System. One of the most important uses of lunar water is to produce H2 and O2 for rocket propellants by electrolyzing the H2O and liquefying the resulting propellant for rockets and lunar transportation. To successfully design an electrolysis and storage plant that achieves industrial production goals of 170 or more mT of H2 per day, while minimizing energy consumption and system mass, it is necessary to perform trade studies employing both systems engineering and thermo-fluid simulation, benchmarked by empirical test data.

Using data from an empirical test campaign employing solid-oxide electrolysis cell (SOEC) technology in a cryo-vacuum chamber, system models have been benchmarked to simulate water electrolysis and liquefication in the lunar environment at the lab scale. These models, in turn, have been scaled up and employed in trade studies to determine energy consumption and system mass on the industrial scale, using a variety of scales and combinations of electrolysis stack and balance of plant components to determine the optimal architecture for such a pilot plant. This analysis has been also compared to simulation of similar H2-production architectures employing alternative electrolysis technologies of proton electrolyte membrane (PEM) and alkaline electrolysis cell (AEC) technology, also benchmarked using available empirical test data. Additionally, the system architectures in this paper are qualitatively evaluated for system engineering metrics of potential reliability, maintainability, and availability, as well as the likely feasibility of deployment of such a system on the Moon and operation of it in the lunar PSRs.

The results of this paper lay out a recommended system architecture for in-situ H2 production from lunar water based on these physical and systems engineering considerations, as well as a recommended high-level mission architecture for deployment.

Keywords: space transportation systems
new equipment concepts
mining and processing automation
fuel production
hydrogen production
resource processing

04:20 PM **9662 - Volatile Production Model from Optically Spalled CI/CM Asteroid Simulant**

Timofey Broslav - PhD Candidate, Chris Dreyer - Advisor, Joel Sercel - Inventor/Sponsor

Abstract: On April 20, 2021 an opaque golden box over 100 million miles from Earth achieved a pivotal milestone in space exploration. This was the day that the Mars Oxygen ISRU Experiment (MOXIE) produced oxygen from the Martian environment – the first case of In-Situ Resource Utilization (ISRU) achieved on another planet. The impacts of such a field of technology cannot be overstated. Having the ability to procure water from other bodies than the Earth will greatly reduce space launch costs, cost of space missions, and open up pathways to sustainability both off and on the Earth. The Optical Mining method – developed by the Trans Astronautica Corporation – aims to harness the power of the sun to extract such volatiles from Near Earth Objects (NEO’s), and eventually other asteroid bodies for use as propellant feedstock or consumables. This method of mining delivers a focused beam of sunlight on the surface of a 1 – 10 m carbonaceous CI/CM asteroid to induce the thermo-mechanical phenomenon of spallation. The high irradiance from the beam simultaneously spalls the surface into fragments and dehydrates the material therein to produce volatiles such as water.

This paper focuses on a portion of a model aimed to further the understanding of Optical Mining, and its application to produce water from Carbonaceous Chondrite Asteroids. Current testing performed with CI/CM asteroid simulant and a Xenon arc lamp/reflector system at the Colorado School of Mines Center for Space Resources lab indicates low water production rates (10 – 55 g/hr). It is postulated that this may be a result of the low uniaxial compressive strength of the tested simulant (~140 kPa), which facilitates spallation to occur at temperatures below the threshold of complete dehydration of the constituent mineral. However, spall fragments are ejected from the surface of the simulant and spend time being heated in the path of the beam. This subsequent faster heating of the ejected spalls may account for water produced from dehydration. Hence, a volatile production model has been created to account for ejected spall fragments in the light path and predict the water that should be produced from the dehydration reactions that would be incurred by these spalls. The model also incorporates the effects of a variety of unknowns, including a size distribution in the spalled particles, their paths through the beam, and their ejection velocities. Model results are then compared to experimental results to assess if the volatiles produced from the ejected spalls align with what has been experimentally observed or if other possible explanations for the low water production should be investigated. Results from the model will also aid in the assessing optimal irradiance for both spallation/volatile dehydration of a body. Although our knowledge of the mineral compositions of Asteroids is in flux, thus the simulant not containing all of the minerals likely to be encountered on such asteroids, this model still advances the understanding of volatile production using the Optical Mining Method on a body with a known mineral composition.

Keywords: Asteroid Mining
ISRU
Optical Mining
Mining

04:40 PM **6887 - Moon Trades: Unlocking the Potential of Lunar Mining and Resource Utilization**

Eronim Mihoc - Moon Trades, Madison C. Feehan - Moon Trades, Wintta Ghebreiyesus - Moon Trades, Fabio Giuseppe Bisciotti - Moon Trades

Abstract: Moon Trades, a leader in lunar and Martian mining, is redefining space exploration through innovative technology and STEM education. Our strategy integrates advanced autonomous robotics, AI, VR, and AR into our ASTRAL and PEBBLE systems, designed for efficient extraterrestrial surveying and exploration. We aim to transform the identification and analysis of lunar and Martian terrains, optimizing resource extraction for future space missions. Emphasizing sustainability and education, Moon Trades aligns with NASA and ESA's strategic goals, blending practical space applications with academic learning. Our current progress underscores our commitment to developing partnerships and engaging in global outreach. This whitepaper highlights Moon Trades' commitment to sustainable space exploration and education, showcasing our dedication to the future of lunar and Martian resource utilization.

Keywords: Lunar Exploration
Autonomous Rover
Artificial Intelligence
Sensor Technology
3D Digital Models
Data Analysis
Mining
STEM Education
Global Space Community

05:00 PM **8313 - EURO2MOON: Leverage lunar resources exploration to foster international collaboration and benefit sustainability in Space and Earth**

Pierre-Alexis Joumel - Airbus Defence and Space, Bertrand Baratte - Air Liquide

Abstract: For more than 50 years now, humans have not come back on the Moon but remained in LEO thanks to international orbital stations. However, new programs have been raised recently targeting a return of humans on the Moon in the 2020s with an ambitious goal of having a permanent presence. Based on the ISS experience, it will require a sustainable approach of operations in Space. This trend already began with the development of private launchers that lower the cost for accessing Space. From now on, a new step must be overcome to allow a

sustainable and permanent human presence on the Moon. According to AIAA 5 technical challenges have been identified:
● Space transportation: reliable and affordable Space transportation between Earth and Moon. It also includes the mobility on the Moon with rovers for instance;
● ISRU: possibility of using resources present on the Moon such O2, H2O, metal;
● Long-term habitation: habitat for allowing permanent life of humans. It especially addresses the challenge of life support and virtuous closed cycle operations;
● Power generation & Energy management: production and storage of energy to sustain lunar night and provide power for operations on the Moon;
● Human health: monitoring of human health and limiting effects of radiations, microgravity, ...
To overcome those challenges, many capabilities from Space and non-Space actors will need to be put together. To that end, the EURO2MOON Industrial association has been created in 2021, to position European Industry as a reference partner of the rising cis-lunar economy, through the exploration and the implementation of transversal Space resources value chains (for instance, to serve the purpose of long duration transportation, life support, energy production & storage, construction of local infrastructures…).
Airbus Defence and Space, with its wide Space competencies and experience, Air Liquide, with its long standing experience on gas management (cryogenics, energy, …) and ispace, with its leading expertise in lunar rover, co-founded this initiative to tackle these challenges by focusing on the end to end value chain of oxygen and H2O (that could form H2 and O2) on the Moon. This group of industrials has been already joined by ESRIC (the European Space Resources Innovation Center), CEA (the Centre d'Energie Atomique), Arthur D. Little and Spartan Space, and the association has been announced at the IAC 2022. Indeed, the water and oxygen molecules are key for many challenges, and could serve the purpose of Space transportation (propellant and mobility), ISRU (water recovery), Long term habitation (life support) and energy management (FC and Electrolyzer), in space for space. This would completely reinvent the architecture of space missions, allowing to go deeper in space, stay longer, refuel the spacecrafts, extend their lifetime and consequently reduce the debris, reduce the total cost of the missions… for the benefit of more sustainable space operations. This could also benefit international collaboration as all Nations will need these new services in space (energy, refueling, life support).
EURO2MOON is organized in specific Workings Groups focusing on key topics such as power, oxygen and water value chain, in order to jointly work on common roadmaps, recommendations and demonstration to be proposed to European stakeholders. EURO2MOON members can contribute to solve some technological challenges and initiate a European industrial ecosystem.
This presentation is the opportunity to present the results of the activities of the EURO2MOON technical Working Groups to the global community, which aim to become the main platform of exchange for a common industrial roadmap for Space resources value chains implementation and the enabler of industrial demonstrations in Europe.
EURO2MOON could also be available to join a round table / panel during Earth&Space2024.

Keywords: ISRU
Space Resources
Europe
Value Chain
EURO2MOON

05:20 PM **4923 - Outcompeting Starship: the cost of lunar-mined rocket propellant will drop faster than the cost of launching it from Earth**

Philip Metzger - UCF

Abstract: A thorough techno-economic analysis has been performed for mining lunar ice and selling it as rocket fuel in various locations throughout cislunar space. The analysis considers different mining architectures and orbital transportation scenarios. It is often claimed that reusable launch vehicles like Starship will lower launch costs so low that space mining will not be competitive. This neglects several key factors. First, lower launch cost means the cost of lunar capital will also drop proportionately. Second, lower reliability will be optimal when transportation costs drop, and this has a strongly nonlinear effect on cost. Third, rocketry is near the end of a 100-year learning curve to lower cost, whereas lunar mining is at the beginning of that learning curve. Fourth, the opportunity cost of launching propellant from Earth makes it non-competitive against a lunar competitor. Fifth, environmental factors will drive advantage toward in-space industry. The analysis considers all these factors and shows that over a period of just a few years Lunar propellant should outcompete Earth-launched, perhaps even in Low Earth Orbit. The analysis also considers spares/repairs strategies, development of artificial intelligence, and support of Mars missions. Different market sizes are shown to have only a minor effect on the results. This analysis should settle the question whether space resources can be economic, even with plummeting launch costs. The answer is a resounding yes.

Keywords: Lunar mining
Space mining
Space economics
Lunar propellant

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Wednesday April 17, 2024: Late Afternoon Session

Session Title: Applications of Artificial Intelligence and Machine Learning for Earth and Space Systems
Session Co-chairs: Dexter Johnson, Ph.D. NASA Glenn Research Center, Cleveland, OH and Siddharth Parida, Ph.D. (Embry-Riddle Aeronautical University)
Room 128

03:40 PM **1783 - *Temporal Deep Learning for Crack Pattern Classification Using Acoustic Emission Signals***

Donghuang Yan - Changsha University of Science and Technology, Shuo Wang - Changsha University of Science and Technology, Wenxi Wang - Hunan University

Abstract: Crack pattern classification (tension or shear) plays a crucial role in understanding and predicting potential failure modes of civil structures. Acoustic Emission (AE) is a passive structural health monitoring technique based on stress waves generated by structural cracks, commonly used for crack detection and classification. Traditional analysis methods treat AE signals as isolated individual entities, potentially neglecting the temporal relationships between signals. However, crack propagation is a continuous process, and the crack's growth rate and direction are influenced by time, which is reflected in the temporal domain.
this paper presents TemporalAE-Net, a deep learning framework, that considers temporal information for the crack pattern classification. The framework consists of four main steps, namely the signal combination, one-dimensional convolution, attention mechanism, and multi-layer perceptron. AE signals are first combined into a two-dimensional temporal matrix as the input to the network. One-dimensional convolutional kernels are employed to extract local features without compromising the temporal structure of signal groups. The extracted features are then passed through a self-attention mechanism to capture global correlations. Finally, a multi-layer perceptron serves as a classifier to output the final prediction results. To train the deep learning model and assess its performance, experiments are conducted using small-scale concrete specimens subjected to tension and shear tests to obtain corresponding AE signals. Additionally, four-point bending tests on a concrete beam are used to verify the proposed model's generalization performance.
The results demonstrate the effectiveness of the proposed temporal network model in identifying crack patterns.TemporalAE-Net achieved a classification accuracy rate of 100% on 12 test specimens. Furthermore, in the four-point loading tests on RC rectangular beams, the model's predictions align well with existing research findings. This performance validates TemporalAE-Net's excellent generalization ability on previously unseen data.Impressively,The TemporalAE-Net model excels in capturing AE signal dynamics using its unique temporal design. Its attention to critical time points showcases its robustness and alignment with human analytical skills.
The primary innovation and contribution of this paper lie in the proposal of a deep learning framework that considers temporal information from AE signals. The framework allows multiple AE signals on the time sequence, rather than individual ones, as inputs to the network. By combining signals into a two-dimensional temporal matrix and introducing a self-attention mechanism, the framework effectively enhances crack pattern classification accuracy. This

approach significantly outperforms the traditional methods that treat AE signals individually and effectively utilizes the temporal continuity of AE signals, enabling the network to accurately identify different crack patterns with excellent generalization performance.

Keywords: Structural health monitoring
Acoustic emission signals
Crack pattern classification
Deep learning framework

04:00 PM **2057 - Physics Informed Neural Network for Inverse Estimation in Presence of Sparse Data**

Anthony G. Lore Starleaf - Department of Aerospace Engineering, Embry Riddle Aeronautical university, Siddharth S. Parida - Department of Civil Engineering, Embry Riddle Aeronautical University, Souvik Chakraborty - Department of Applied Mechanics, Indian Institute of Technology, Delhi, Georgios Apostolakis - Department of Civil, Environmental and Construction Engineering, University of Central Florida, Nidhish Jain - Dassault Systems Simulia Corp.

Abstract: Accurate and efficient characterization of system parameters are pivotal for design and analysis of both terrestrial and extra terrestrial civil engineering structures. To this end, this research focuses on developing a machine learning framework that fuses physical laws with sparse dynamic data to inversely characterize physical systems. A finite element based physics informed neural network (FE-PINN) algorithm is proposed. It is hypothesized to inversely estimate system parameters from sparse data accurately and efficiently. The algorithm uses governing physics equations posed in their weak form in the loss function used to train the neural network along with the usual data loss term used in traditional neural networks. Effectiveness of the proposed framework is demonstrated numerically, by accurately estimating the elastic modulus of a 5m × 10m soil column using dynamic response obtained from the system. Even though the verification of the framework is numerical and simplistic, but the success provides a sense of optimism to extend this work to more complex geotechnical as well as structural engineering problems.

Keywords: Inverse problem
Physics informed neural networks
Site characterization

04:20 PM **5485 - Decision tree approach to interfacial debonding detection for steel-concrete-steel structure by impulse-response measurement**

Shiyu Gan - Department of Civil Engineering, Tsinghua University, Xin Nie - Department of Civil Engineering, Tsinghua University, Yuanyuan Li - Faculty of Infrastructure Engineering, Dalian University of Technology, Hongbing Chen - School of Civil and Resource Engineering, University of Science and Technology Beijing

Abstract: Steel-concrete-steel (SCS) composite structure, consisting of a sandwiched concrete core connected to two steel faceplates, has been proposed and applied in infrastructures for its excellent mechanical properties in high stiffness, impact resistance, and good energy absorption capacity. For instance, the Shenzhen-Zhongshan Crossing-sea Link in China (Shen-Zhong Link), which is the first large-scale steel shell concrete immersed tunnel in the world, is a typical application of SCS. However, the interfacial debonding defects between steel plate and concrete core significantly threaten the integrity of SCS and the service performance composite structure. However, the most widely-used nondestructive testing methods for detecting the interfacial debonding defects were conducted in experimental conditions where the thicknesses of steel objectives were less than 10 mm. For steel plates with thicknesses higher than 10mm, the efficiency and accuracy of conventional technologies are not satisfying for in-service projects.

Consequently, there is an increasing interest in developing a more reliable and precise debonding detection technique.
In concept, the vibration mode of the steel plate in debonding area differs significantly from that in the healthy area, resulting from the loss of constraint of concrete. Accordingly, apparent changes in vibration characteristics of steel plates can be detected, preliminarily revealing the feasibility of debonding detection based on vibration analysis. For impulse-response (IR) test, it becomes more difficult to excite effective vibration of steel plates, which makes it challenging to achieve high-efficiency interfacial debonding identification. To improve the precision of IR measurements, a novel percussion approach based on machine learning algorithm of the decision tree is developed to process and classify obtained vibration signals.
To validate the efficiency of the nondestructive method developed in this study, a concrete cubic specimen reinforced by steel plates with four different thicknesses varying from 10 mm to 40 mm were designed for experimental study. Herein, the dimension of the artificial debonding defect was set to 50 mm×50 mm, 100 mm×100 mm, 150 mm×150mm, and 200 mm×200 mm, respectively. The detection system mainly includes an impact hammer, a high-frequency precision accelerometer, and a data acquisition instrument. Based on the collected data from the above-mentioned detection system, the data pre-processing of normalization considering different hammer forces applied in every manual strike, and then the several damage indexes (DI) from the time domain and frequency domain were established for the damage prediction. Furthermore, for fully mining the data information from massive vibration data, the decision tree was adopted for categorizing data, and showed prospective application in comparing the different indexes to seek a more optimal DI for defect identification. On the basis of the sample library from the experimental measurements, the prediction accuracy of the mixed DI proposed in this study was quite high. The research findings also indicate that the novel percussion approach is capable of accurately distinguishing the specific location of defect and health regions in SCS with thick steel plates. Aided by an efficient machine learning algorithm, the interfacial debonding detection for SCS structure with thick steel plates can be achieved, which also presents a broad prospect in practical applications.

Keywords: Steel-concrete-steel composite structure
Interfacial debonding
Impulse-response
Decision tree
Damage index

04:40 PM **1604 - Experimental study on interface debonding detection and visualization in grouting jacket connection of off-shore wind turbine structures with surface wave measurement**

Qian Liu - College of Civil Engineering, Huaqiao University, Bin Xu - College of Civil Engineering, Huaqiao University, Jiang Wang - School of Civil and Resource Engineering, University of Science and Technology Beijing

Abstract: Interface debonding between high-strength grouting material and inner surface of steel tubes of grouting jacket connections (GJCs) widely used in offshore wind turbine supporting structures negatively affects their mechanical behavior. In this paper, an interface debonding defects detection and visualization approach for scale GJC specimens using surface wave measurement is proposed and experimentally verified. Two scale GJC specimens with mimicked interface debonding defects of different dimension are designed, and piezoelectric lead zirconate titanate (PZT) patches are mounted on the outer surface of the steel tubes as actuators and sensors. Surface wave is measured with a one pitch and one catch (OPOC) configuration. Results show that the wavelet packet energy (WPE) of surface wave measurement of the PZT sensor in the travelling path with an interface debonding defect is larger than those without an interface debonding defect. To further visualize the region of debonding, a one pitch and multiple catch (OPMC) configuration is employed and abnormal value analysis on the WPEs of each PZT sensor measurement with identical measurement patch is performed. Interface debonding is visualized based on the regions covered by the surface wave traveling paths with abnormal measurements and meets the locations of the mimicked defects in the specimens.

Keywords: Grouting
Piezoelectric ceramics
Surface wave
Debonding
Wavelet packet energy
Experimental and numerical study

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Wednesday April 17, 2024: Late Afternoon Session

Session Title: Terrestrial, Lunar, and Martian Spaceports – Landing and Launching Pads and Supporting Infrastructure

Session Co-chairs: Jennifer Edmunson, Ph.D. (NASA Marshall Space Flight Center, Huntsville AL); and Mike Fiske, Ph.D. (Jacobs Engineering/NASA Marshall Space Flight Center Huntsville, AL)
Room 117

03:40 PM **2209 - *Comparative Evaluation of Lunar Regolith-Based Tiles for Lunar and Launching Pads: Static Load and Thermal Performance Analysis***

Shezreen Khan - San Diego State University, Sama Ahmed - San Diego State University, Eduardo Bonilla - San Diego State University, Aina Narvasa - San Diego State University, Marta Miletic - San Diego State University, Douglas Cortes - New Mexico State University

Abstract: As space agencies and private companies increasingly focus on lunar exploration and potential human settlement, the need for robust and sustainable lunar infrastructure becomes paramount. Landing and launching pads are critical components of lunar infrastructure, providing a stable surface for spacecraft operations. Thus, developing suitable materials and manufacturing methods for these pads is crucial to ensure safe and efficient lunar missions.
The main objective of this research study is to investigate the structural and thermal performance of two distinct types of tiles designed for lunar and launching pads. The tiles were subjected to rigorous testing under static load conditions and evaluated for their thermal performance to simulate rocket landings on the lunar surface. Static load tests were conducted to evaluate the structural integrity and load-bearing capacity of the tiles. The results indicated that both types of tiles showed satisfactory strength and resistance to deformation under various load conditions. Additionally, thermal performance analysis was performed to assess the tiles' ability to withstand the extreme temperature variations experienced during rocket landings. The findings revealed that both types of tiles exhibited excellent thermal stability and maintained their structural integrity under thermal stress.
Based on the outcomes of the study, it can be concluded that both types of lunar regolith-based tiles demonstrated promising results in terms of their static load-bearing capacity and thermal performance. These findings contribute to the development of reliable infrastructure for future lunar missions and pave the way for sustainable lunar surface operations. Further research is warranted to explore the long-term durability, environmental resilience, and scalability of these tiles. Additionally, efforts to optimize their manufacturing processes and enhance their performance characteristics should be pursued to maximize their potential for supporting lunar exploration and settlement activities.

Keywords: Lunar regolith
Lunar and launching pads
Tile performance
Static load testing
Thermal performance

Rocket landing simulation

04:00 PM **2518 - A Comprehensive Analysis of Autonomous Construction of Lunar Landing Pads (LLPs) Using a Network of Small Robots**

Sivaperuman Muniyasamy - University of Arizona - SpaceTREx, Jekan Thangavelautham - University of Arizona - SpaceTREx

Abstract: The quest to return humans to the moon and create a long-term human presence on the moon has been accelerated by NASA's Artemis Program. The international efforts to establish a permanent base on the moon have taken a new shape in recent decades. This endeavor not only opens doors for public and private agencies to advance space development activities but also emphasizes the need for critical infrastructures such as habitats, storage modules, landing pads, and blast walls in establishing a permanent lunar base. At the early stages of lunar base development, a safe and reliable landing pad becomes a critical element to facilitate continuous spacecraft landings and launchings. However, constructing a landing pad on the lunar surface presents various challenges due to hazardous environmental conditions: micrometeoroid bombardments, solar and cosmic radiation, lunar dust, and extreme temperature fluctuations between lunar days and nights, which pose significant risks for human operations. Moreover, the lunar regolith consists of loose regolith with properties like crushed glass, making it extremely fine and abrasive. We propose a team of small autonomous robots operating in chain configurations for site preparation, excavation, and landing pad construction. The chain configuration has advantages compared to a single robot or decentralized multirobot system in leveling and compacting the surface observed in our previous work. Further, we are designing tool kits: excavators, cutters, compactors, and graders tools for various tasks associated with site preparation and landing pad constructions. Modeling the robot's interaction with the lunar regolith is vital to analyze and evaluate the performance of robots. Thus, we intend to model the robot-lunar soil interaction and analyze robots' performance while performing tasks: site preparation, leveling, and compacting in the muti-physics dynamics software. Moreover, we evaluate the feasibility of modeling and simulating landing pad construction using single and multi-robot configurations. It is important to evaluate the performance metric and quality measures, such as analyzing the Return on Investment (ROI), energy cost, and resource cost associated with the landing pad construction to utilize the resources effectively. In addition to this, a detailed study is presented on identifying a few key requirements for autonomous landing pad construction, including the need for robust and reliable robots, efficient energy management, and structural requirements to withstand the harsh lunar environment and cyclic loading due to continuous spacecraft's landings and launches. We aim to test and evaluate the robot's performance in the sandbox facility in a control volume using river wash sand. Moreover, we will design, fabricate, and test a variety of landing pad models with commercially available low-cost components as a lunar simulant to understand the different inner layer configurations that can meet the landing pad requirements. This is essential for selecting landing pad materials and laying the foundation for robots to automate construction.

Keywords: landing pads
Moon
autonomy
lunar base
construction

04:20 PM **5905 - Constructing Lunar Landing Pads from Regolith Feedstocks Fused by Concentrated Solar Energy**

Alan Carter - Outward Technologies, Andrew Brewer - Outward Technologies, Ryan Garvey - Outward Technologies

Abstract: Outward Technologies conducted a series of physical experiments which showed the feasibility of constructing lunar launch and landing pads from lunar regolith feedstocks using a concentrated solar heat source to fully melt and fuse lunar regolith into a consolidated structure. A series of on-sun tests used a 1000 by 1200 mm Fresnel lens to produce cylindrical specimens 75mm in diameter and ranging in height from 7.5mm to 17.5mm. During specimen production, a bed of lunar highlands regolith simulant CSM-LHT-1 was prepared, and the Fresnel lens was focused onto the regolith surface to create a melt pool. The focal point was then translated across the regolith surface to selectively melt the regolith. Single-layer structures were produced in this manner. For several specimens, an additional step was then taken to produce multi-layer structures. Additional regolith was deposited on top of the previous layer and melted into the lower structure. The solidified material was comprised of mostly crystallized phases with some amorphous regions. Compression tests showed the specimens had an ultimate compressive strength around 25 MPa and a Young's Modulus of 10.3 GPa, both of which were similar to M25 grade concrete. The scan strategies and print parameters tested were found to have little impact on the performance of the LLP specimens, and these parameters could be further optimized to increase construction rate. Load bearing tests were then conducted on the specimens. Specimens were placed on a prepared bed of regolith simulant and loaded to failure at their center via a loading ram to simulate loading by a lunar lander footpad. Next, two sets of analytical plate loading calculations were conducted using the measured mechanical properties and load at failure. The first set of equations identified the peak tensile stress experienced during the load bearing tests. Results showed the specimens had a tensile strength ranging between 6 and 12 MPa, higher than that expected for M25 grade concrete. The second set of plate loading equations considered the expected modulus of subgrade reaction for the surface of the Moon and determined the required LLP thicknesses for various planned lunar landers. For a modulus of subgrade reaction of 5 kPa/cm, the non-compacted subgrade reaction expected on the lunar surface, a regolith LLP 2 cm thick would be able to support a 3.1 metric ton lunar lander supported by a single footpad. For a much higher subgrade reaction of 2,700 kPa/cm which is achievable through additional compaction of the subsurface, a 3.2 cm regolith LLP would be able to support a 1,000 metric ton lander supported by a single footpad. These results showed the feasibility of using concentrated solar power in a print-in-place construction method to produce both single- and multi-layer horizontal structures suitable for LLPs from a regolith feedstock without the need for binders or consumables from Earth.

Keywords: Concentrated Solar Energy
Landing and Launch Pad Construction
Additive Construction
In-situ Resource Utilization

04:40 PM **9162 - SITE PREPARATION FOR A LUNAR LAUNCH AND LANDING PAD**

Samuel Ximenes - Astroport Space Technologies, Barney Gorin - GoVentures, Sazzad Shafique - The University of Texas at San Antonio, Ibukun Awolusi - The University of Texas at San Antonio, Chinedu Okonkwo - The University of Texas at San Antonio, Mark Jaksa - University of Adelaide, Andy Thomas Centre for Space Resources, Gary Bastin - KBR, Oskar Fryckowski - Four Point, Marek Wilgucki - Four Point, Codie Petersen - Asteres, Joshua Torgerson - Asteres, Jaret Matthews - Venturi Astrolab, Joe Redfield - Astroport Space Technologies, Ronald Wells - Astroport Space Technologies, Lutz Richter - Softserve, Damian Pietrusiak - Wrocław University of Science and Technology, James Johnson - Astroport Space Technologies, Reynaldo Trevino - Astroport Space Technologies, Donald Hooper - Astroport Space Technologies

Abstract: Landing on unprepared lunar surfaces can excavate tons of regolith, send high-velocity lunar regolith particles kilometers from the landing site and inject particles into lunar orbit.

Therefore, lunar launch and landing pads (LLPs) are needed to protect surface and orbital assets from debris damage and provide solid, impervious surfaces for multiple landings near a permanent lunar facility.
Civil engineering and construction processes for lunar bulk regolith manipulation remain at low technology readiness levels (TRLs). Design requirements and functional capabilities of bulk regolith-based lunar infrastructure are not well defined. Astroport Space Technologies is a space technology and construction company focused on using lunar regolith for in-situ resource utilization (ISRU) to create launch and landing pads for large, human-scale lunar landers and other lunar surface infrastructure. Astroport leads an industry and academia research team for advancing the state-of-art with investigations of geotechnical engineering and civil engineering processes for bulk regolith manipulation techniques, using a "regolith works" toolset for the construction of a LLP.

A Concept of Operations (CONOPS) for Astroport's approach to site preparation, excavation and site leveling for constructing an LLP is described. The CONOPS is based uniquely on Astroport's landing pad brickmaking and placement technology using our Lunatron BrickLayer system for constructing planar surfaces. The BrickLayer technology enables single-step lunar regolith melting, brick forming and placement without use of grouts or mortar for landing pad creation, or for any flat hardened surface area such as roads or foundations. Near-term efforts will address architectures for automating these operations.

Keywords: lunar launch and landing pads
lunar construction
lunar infrastructure
ISRU

05:00 PM **6544 - Mobile Launcher Refresh for Kennedy Space Center**

Kevin MacLeod - Bechtel NS&E, Pete Carrato - Bechtel Corporation, Luis Moreschi - Bechtel NS&E

Abstract: The Mobile Launcher 2 (ML2) is a new ground support structure developed for NASA's Artemis Program. The 380-foot tall ML2 tower will be used to assemble, transport, and launch the largest configurations of NASA's Space Launch System (SLS) rocket and Orion spacecraft. ML2 is significantly larger and supports a vehicle nearly 1 million pounds heavier than its predecessor Mobile Launcher 1 (ML1). Both ML1 and ML2 employ the same Crawler Transporter (CT) and are weight constrained by its lifting capacity.
As a portable structure at the Kennedy Space Center, ML2 must interface with existing NASA infrastructure, including three legacy facilities and the CT which moves it between these facilities. The Block 2 configuration of SLS is one of the largest rockets currently in the world, weighing up to 6 million pounds fully fueled. It will blast ML2 with 9.5 million pounds of thrust from its two solid rocket boosters and four RS-25 engines. Critical components of the structure will be exposed to plume and vibro-acoustic loading, reaching pressures around 150psi and temperatures around 2,200 °F. Concurrently, half a million pounds of water is passing through the structures sound suppression system and 400,000 gallons of water is released onto the structure in 40 seconds. The extreme environment of the launch event controls much of the structural design. Even in the absence of a launch, the coastal Florida landscape provides significant design and material challenges including hurricanes and one of the world's most corrosive environments. In all more than 6000 load combinations are evaluated in the ML2 Global Analysis.
The most impactful design considerations required producing a lightweight structure that complied with stringent stiffness requirements governing the dynamic interaction between the spacecraft and the tower. Advanced analysis techniques were utilized to identify and optimize critical members in the tower. High strength API steel pipe typically used in offshore rigging platforms is used for tower columns and vertical bracing. Complex piping connections are

manufactured as steel castings to simplify design, reduce weight, and improve joint stiffness. The tower's construction sequence is built into the analysis model to capture residual stresses from self-weight and accurately trace dead load distribution through the different support conditions. The ML2 structural design is backed by a robust analysis validating the structure's ability to support the variety of loads and conditions necessary to meet the goals of the Artemis Program. ML2 is the launch point to return humans to the lunar service, establish a lunar outpost, and lunar gateway to test and qualify technologies needed to travel to Mars.

Keywords: Mobile Launch Tower
Rocket Launch Environment
Blast Loads
Weight Controlled
Mobile Structures
Cast Connections
NASA Artemis
NASA SLS

05:20 PM **7304 - On The Incorporation of Both Function-Driven and Topology Optimization in The Development of Lunar Launch & Landing Pads**

Luke Scharber - NASA/Marshall Space Flight Center, Michael Fiske - Jacobs Space Exploration Group

Abstract: In the design of additively manufactured structures, there can be a constant battle between focusing on function-driven optimization and topology optimization in an attempt to improve a products ability to meet all requirements.
Function-driven optimization is defined as the process of identifying the best design parameters that satisfy project functionality requirements. Function-driven optimization is typically implemented by a designer(s) who, instead of computational limitations, has human bias for the input or inputs determined. On the other hand, topology optimization is defined as a mathematical method that optimizes material layout within a given design space, for a given set of loads, boundary conditions, and constraints with the goal of maximizing the performance of the system. In topology optimization, the work is defined by the limited mathematical inputs and computationally available goals/restraints. If not evaluated simultaneously, these two approaches can result in fundamentally different design concepts meant to address the same requirements.
NASA's Artemis program includes the development of a base camp near the lunar South Pole. After site selection is made, one of the first infrastructure elements needed will be a launch and landing pad. The construction of such a pad will prevent damage to nearby structures from plume-surface interaction (PSI) while also providing a stable platform for the lander. These benefits reduce the required distance between the established landing zones and other settlement infrastructure.
In this paper, the authors evaluate the requirements associated with lunar launch & landing pad development, application of both functional and topological optimization techniques, methodologies to combine the two techniques, and potential impacts on final design of such a pad.

Keywords: Lunar Infrastructure
Landing Pads
Topology Optimization

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Wednesday April 17, 2024: Late Afternoon Session

Session Title: Manufacturing, Development, and Modeling for ISRU-oriented Infrastructure Materials and Construction Technologies on the Moon and Mars

Session Co-chairs: Yong-Rak Kim, Ph.D., P.E., F. EMI, F.ASCE (Texas A&M University, College Station, TX); Xijun Shi, Ph.D., P.E. (Texas State University, San Marcos, TX); Hyu Shin, Ph.D. (Korea Institute of Civil Engineering and Building Technology, South Korea)

Room 124

03:40 PM **485 - *Fiber-Reinforced Lunar Geopolymers for Future Lunar Construction***

Solomon Debbarma - Indian Institute of Technology Bombay,, Xijun Shi - Texas State University, Anthony Torres - Texas State University, Mehrab Nodehi - University of California Davis

Abstract: Habitation of off-world environments, like the Moon, will require many unique construction approaches, such as additive construction. In-situ resource utilization is very important to not only support additive construction on the Moon, but to also minimize weight of transportation. The work outlined in this study presents a possible solution to supporting lunar additive construction by the formulation of fiber-reinforced geopolymer binders using lunar regolith simulants. Two types of regolith simulants were utilized to synthesize the fiber-reinforced geopolymers developed in this study (i.e., Lunar Mare Simulant (LMS-1D) and Lunar Highlands Simulant (LHS-1)). The material properties and variables investigated were the simulant type, flowability, the effect of curing temperature on compressive strength, fiber type, and flexural strength. The results were supplemented with chemical and microstructural analysis. It was observed that the LHS-1 geopolymer exhibited higher compressive strength compared to that of the LMS-1 geopolymer. High-temperature curing at 93°C and 5% RH for 72 h was found to show a significant strength development on the LHS-1 geopolymer. However, the LMS-1 geopolymer did not show any significant strength development irrespective of curing conditions. The combination of equal proportions of LMS-1 and LHS-1 produced a geopolymer with a flow value of 94 mm, compressive strength of 29.75 MPa and flexural strength of 2.32 MPa when cured at high-temperature. The addition of basalt fibers and human-hair fibers improved the flexural strength by up to 32% and 15%, but reduced the compressive strength. This is validated by SEM analysis which confirms that the fibers act as nucleation sites to significantly improve the flexural strength and microstructure of the lunar geopolymer.

Keywords: lunar construction
geopolymer
basalt fiber
human hair
regolith simulants

04:00 PM **2115 - Additive manufacturing of polyether ether ketone (PEEK)/ lunar regolith composites via fused filament fabrication**

Mohammad Azami - Concordia University, Pierre-Lucas Aubin-Fournier - Concordia University, Krzysztof Skonieczny - Concordia University

Abstract: The NASA Artemis Program is propelling progress in space settlement and explo- ration. In-space manufacturing (ISM) plays a crucial role in extended space explo- rations, and additive manufacturing (AM) holds significant promise. Polyether ether ketone (PEEK) is an excellent material for lunar environments and can be 3D printed using fused filament fabrication (FFF), which offers advantageous versatility over other techniques. Incorporating lunar regolith into PEEK can reduce ISM costs. This study focuses on FFF of PEEK/regolith composites and compares them with pure PEEK and PEEK with carbon fiber. Higher solid material content presents challenges during extrusion, leading to increased sample porosity. The addition of 20 wt% carbon fiber enhances tensile strength by 8.37%, whereas introducing 15 and 30 wt% lunar regolith reduces tensile strength by 14.63% and 26.78%, respectively, resulting in more brittle fractures and reduced elongation at break. These findings hold significant implications for advancing additive manufacturing in lunar environments and in-space manufacturing.

Keywords: In-space Manufacturing
Additive Manufacturing
In-situ Resource Utilization
Regolith
Polyether Ether Ketone (PEEK)
Moon
Space Exploration

04:20 PM **3218 - Vacuum microwave sintering of lunar regolith simulant for lunar construction**

Young-Jae Kim - Korea Institute of Civil Engineering and Building Technology, Taeil Chung - Korea Institute of Civil Engineering and Building Technology, Li Zhuang - Korea Institute of Civil Engineering and Building Technology, Hyunwoo Jin - Korea Institute of Civil Engineering and Building Technology, Sun Yeom - Korea Institute of Civil Engineering and Building Technology, Jangguen Lee - Korea Institute of Civil Engineering and Building Technology, Hyu-Soung Shin - Korea Institute of Civil Engineering and Building Technology

Abstract: Humans are expected to return to the lunar surface for long-term exploration in the near future. More countries than ever before are actively engaged in space exploration programs, with a focus on sustainable lunar presence and lunar exploration. In order to support sustainable human and robotic exploration in the extreme lunar environment, including cosmic radiation, temperature variations, high vacuum conditions, and micrometeorite impacts, infrastructure such as habitation and ISRU facilities must be built.

Our research aims to develop technologies for the production of construction materials needed to build infrastructure on the lunar surface, such as landing pads, blast wall, roads, and habitation. The most realistic approach to producing construction materials on the lunar surface is to utilize lunar soil and microwave heating has been proposed as one of the suitable methods for sintering lunar soil.

In this study, we focused on manufacturing construction blocks using microwave sintering method in a vacuum environment. A lunar regolith simulant (KLS-1) was subjected to SiC susceptor-assisted microwave sintering at various temperatures under vacuum conditions. Optimal sintering conditions such as preheating treatment, temperature, and heating rate were determined to obtain homogeneous sintered blocks under vacuum conditions. As the sintering temperature increased from 1060°C to 1100°C, the density increased, the total porosity decreased, and the mechanical strength increased as a result. The samples sintered at 1080 and 1100 °C have a mechanical strength similar to that of terrestrial concrete. Under the same sintering temperature conditions, samples sintered in vacuum have higher density and mechanical strength than those sintered in air. In general, denser structures can be produced under vacuum conditions because the pores can shrink during sintering. In addition, the spatial distribution of local porosity was investigated based on X-ray CT images to assess homogeneity. For samples sintered at 1060, 1080, and 1100 °C, very homogeneous sintered samples were produced. Therefore, microwave sintering is expected to be a promising method for building infrastructure to support sustainable lunar exploration.

Keywords: ISRU construction
Infrastructure Materials
Vacuum microwave sintering
lunar regolith simulant
Physical property
Mechanical property

04:40 PM **4916 - Spark Plasma Sintering of NUW-LHT-5M Lunar Highland Simulant: Effects of Sintering Temperature on Physical, Mechanical, and Microstructural Properties**

In Kyu Jeon - Texas A&M University, Yong-Rak Kim - Texas A&M University

Abstract: Considering the in-situ resource utilization (ISRU) concept in space exploration, spark plasma sintering (SPS) is a potential densification method to produce structural components as it can produce high-density, high-strength material using solely lunar regolith. To achieve the future lunar mission near the south pole, it is essential to develop proper densification techniques using lunar highland soil similar to that region. This work used NASA’s newly developed NUW-LHT-5M lunar highland simulant for SPS by varying sintering temperatures. To investigate the effects of sintering temperature, which is the most significant SPS factor, several laboratory measurements, including density, hardness-stiffness from nanoindentation, and microstructure characteristics from scanning electron microscopy, were made. Test results demonstrate that (1) the physical, mechanical, and microstructural characteristics are greatly affected by sintering temperatures, and (2) SPS is a feasible sintering method for lunar highland regolith.

Keywords: Spark Plasma Sintering
In-Situ Resource Utilization (ISRU)
Lunar Construction
NUW-LHT-5M
Experimental Characterization

05:00 PM **9475 - Mechanical Properties of Regolith-Resin-Based Composite (RRC) for Off-Earth Construction Utilising In-Situ Resources**

Mohammad Altaf Hossain - The Andy Thomas Centre for Space Resources (ATCSR), The University of Adelaide, SA, 5005, Australia, Scott T Smith - ATCSR and School of Architecture and Civil Engineering, The University of Adelaide, SA, 5005, Australia, T. Tafsi

Abstract: The roadmap of the Australian Space Agency (ASA) is in accordance with the objective of the National Aeronautics and Space Administration (NASA) Artemis programme, which aims to construct durable lunar habitats by utilising indigenous resources to mitigate the expenses and hazards associated with lunar operations. To achieve this objective, it is imperative to focus on the advancement of sustainable structural systems that incorporate affordable construction materials sourced from off-Earth locations, utilising in-situ resource utilisation (ISRU) techniques. Investigating cutting-edge materials and inventive designs has become of utmost importance in the lunar structures domain, especially when functioning in harsh conditions. The trajectory of human space exploration is contingent upon the advancement of sustainable and economically viable construction technologies for extraterrestrial habitats. An approach that shows promise involves utilising in situ resources, specifically regolith, which refers to the regolith found on the lunar surface to create building materials. This study aims to examine the advancement of regolith-resin-based composites (RRC) as a feasible approach for extraterrestrial construction, emphasising its potential advantages and obstacles. Several challenges still need to be addressed in the development of the RRC for extraterrestrial construction purposes. The areas of focus encompass the optimisation of the regolith-binder mixture through the assessment of mechanical properties.

The objective of this study is to create a cost-effective and sustainable lunar construction material known as RRC using lunar regolith simulant as aggregate and resin as a binder. The binder content will be ranged between 15 to 25 % of the weighted mixture. This objective can be achieved through a comprehensive analysis and evaluation of the material's properties and mechanical performance of RRC. A series of mechanical tests will be performed to ascertain the mechanical properties, including compressive strength, flexure strength and tensile strength of the RRC samples.

The utilisation of RRC holds significant potential for the progression of lunar construction through the utilisation of locally available materials. By utilising the ample regolith found on the Moon, the RRC methodology presents an opportunity to transform the construction of lunar habitats significantly. This approach has the potential to enhance sustainability, reduce costs, and ultimately facilitate the establishment of enduring human settlements beyond the confines of Earth. With the ongoing progress of research and technological advancements, the realisation of establishing extraterrestrial settlements constructed using materials obtained from the celestial bodies themselves becomes increasingly feasible.

Keywords: Resin
Regolith
In-situ resources utilisation
Off-earth construction
Regolith-resin-based composite (RRC)
Mechanical properties.

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Wednesday April 17, 2024: Late Afternoon Session

<u>Session Title:</u> Student Paper Finalists III
<u>Session Co-chairs:</u> Robert K. Goldberg, Ph.D., F. ASCE (NASA Glenn Research Center, Cleveland, OH); Krzysztof Skonieczny, Ph.D. (Concordia University, Montreal, Canada)
Room 115

03:40 PM **7406 - *Electrostatic Sorting of Lunar Regolith Simulants for Sustainable Resource Utilization: Modeling and Characterization of Particle Size Distributions***

Fateme Rezaei - University of Miami, Daoru Han - Missouri University of Science and Technology, Jeffrey Smith - Missouri University of Science and Technology, David Bayless - Missouri University of Science and Technology, William Schonberg - Missouri University of Science and Technology, Peter Bachle - Missouri University of Science and Technology, Kyle Newport - Missouri University of Science and Technology, Abdullah Al Moinee - Missouri University of Science and Technology

<u>Abstract:</u> In pursuit of sustainable resource utilization on the Moon, this paper delves into modeling and characterization of particle size distribution (PSD) of lunar regolith simulants in an electrostatic system. A prototype electrostatic sieve was built and tested with four sample simulants mirroring properties of lunar mare and highland regolith. An alternating four-phase (90°, 180°, 270°, 360°) traveling square-wave was utilized for particle-directed transport to model the diverse trajectories of the particles. Numerically, we scrutinized how the distribution functions of the particles are manifested as the electrostatic field propagates, with a focus on three distinct particle ranges (<105, 105-250, 250-500 μm) of four simulants. Results indicated considerable influence of sorting mechanism and control parameters on electrostatic sieve's operation. These parameters encompass column inclination angles (10°, 15°, 20°) and port length (from inlet 10-50 cm) at different excitation frequencies (10, 15, 20 Hz) of power source. We optimized parameters in fitting experimental data and successfully identified the movement of particles under electrostatic field at an average feed rate of 0.18 kg/h (0.05 g/s), however, the existing circular system was ineffective and unable to facilitate sorting and separation of the lunar simulant particles. Overall, the results indicate that while our electrostatic sieve instruments is efficient in moving the regolith simulant particles, its design and operation should be further modified for simultaneous transportation and separation of the particles.

<u>Keywords:</u> Lunar regolith
Size distribution modeling
Electrostatic sieve separator
Extraterrestrial environments
Sustainable resource utilization

04:00 PM **6270 - Inflatable Tetrahedron Rover Concept for Lunar Lava Tube Exploration**

Anna Dinkel - University of Arizona - SpaceTREx, Jekan Thangavelautham - University of Arizona - SpaceTREx

Abstract: Humans will return to the moon in the coming decade with plans of extended exploration. The moon's surface experiences some of the most extreme conditions in the solar system, posing a threat to both humans and robotics. Lunar explorers face large temperature fluctuations, intense radiation, micrometeorites impacts, and challenging terrain. Lava tubes are suspected of stabilizing and protecting from these threats and may be the ideal location for potential lunar bases. Lava tubes are large caverns and tunnel systems formed by lava flow beneath the surface. The Lunar Reconnaissance Orbiter has identified many lunar pits and suspected skylight entrances to lava tubes. Collapsed rock on the surface forms skylights that give access to the underground terrain. Lava tube exploration systems must account for steep drops to reach the tube floor and surface travel over uneven cratered terrain and fine lunar regolith.

Inflatables have been used in many space development and exploration applications. The Mars Exploration Rover mission used inflatable airbags to cushion landing on the surface. Many lunar base concepts use inflatable chambers, as they are cheaper and easier to transport to the moon. Inflatable systems can be compressed during flight to reduce flight costs, leading to a lower mass and volume than non-inflatable systems. Rovers using inflatable wheels can expand to larger diameters, increasing the wheel surface area. More contact with lunar terrain improves traction and mobility over fine sand and large obstacles. Inflatables also provide cushion and protection for the payload when encountering drops.

We propose a tetrahedron rover with large inflatable wheels to maneuver over the lunar terrain and drop into a lava tube skylight entrance. Three inflatable modular wheels are located on each of the four faces of the rover, enabling the vehicle to drive on any side and “tumble” as it travels across uneven terrain. In addition to the wheels, auxiliary inflatables expand to act as airbags, enabling the rover to enter a skylight entrance and fall to the pit floor. The rover can then continue exploring, driving on any face of the tetrahedron. The inflatables protect the rover against thermal, radiative, and impact effects. The tetrahedron rover provides a solution to lunar terrain mobility and skylight lava tube entry and enables the exploration of new lunar features.

Keywords: inflatable rover
lava tubes
exploration
shielding

04:20 PM

148 - LIBS-Raman Multimodal Architecture for Automated Lunar Prospecting

Jérôme Pigeon - Polytechnique Montréal, Pooneh Maghoul - Polytechnique Montréal, Foutse Khomh - Polytechnique Montréal, Richard Boudreault - Polytechnique Montréal, Ahmed Ashraf - University of Manitoba

Abstract: A fundamental aspect of contemporary space programs revolves around optimizing the use of lunar In-Situ resources, known as In-Situ Resources Utilization (ISRU). This strategy has the potential to significantly cut down the immense energy requirements for human space exploration and, equally important, reduce the costs associated with launching satellites into orbit. However, the Moon is largely unexplored from a resource standpoint and needs high-resolution instruments to assess the resource concentration as well as the nature of a sample. Given the vastness of the lunar (sub)surface exploration area and its complexity, a diverse array of instruments is required to establish an efficient and autonomous system for characterizing lunar regolith. This paper aims to propose a multimodal machine learning model developed to identify minerals using Raman Spectroscopy and Laser-Induced Breakdown Spectroscopy (LIBS) instruments based on a multimodal fusion architecture.

Keywords: Lunar Mining
In-Situ Resource Utilization (ISRU)
Automation in Prospecting

Raman Spectroscopy
Laser Induced Breakdown Spectroscopy (LIBS)
Convolutional Neural Networks (CNN)
Multi-modal
Deep-Fusion
Data Fusion
Sensor Fusion
Attention Mechanism

04:40 PM **3435 - Effects of Extreme Daily Temperature on Tall Truss-Type Solar Power Structure on the Moon**

Hernan Cortez Jr - University of Connecticut, Ramesh Malla - University of Connecticut

Abstract: The ability to collect solar energy on the moon is essential for lunar structures, construction systems, and more, to receive the electric power required. NASA has identified the south pole region of the moon as the location for lunar exploration and that structures be built within the very deep and large craters found in this area. However, as the sun is on the horizon of the moon, the inside of these craters do not receive constant sunlight. To overcome this, NASA has envisioned to build a 50-meter-tall tower that would rise above the surface and hold solar arrays powerful enough to supply constant electricity. The lunar environment is extremely harsh. Two key aspects of the extreme environmental conditions are the large temperature extremities and the ground motion caused by moonquakes. For example, at the equator of the moon, the daily temperature can range from 120 C during lunar day time to -130 C at lunar night time. In order to fully understand the effect of these conditions on the designed 50-meter-tall truss-type solar power structure, it is critical to conduct both a thermal and ground/support motion analysis. In this paper, the analyses of the tall solar power truss-type structure have been conducted using Finite Element modeling to determine the structural deformations and stresses due to the applications of extreme temperature loads and ground/support conditions. As the structure will be located within a crater, the solar rays will not reach the portion of the tower encompassed by it; making it important to determine how shadows can alter the effect of the daily temperature. The temperature loads for the shadowed and not shadowed regions of the structure were considered to be the lunar night and day time temperatures respectively. Moonquakes are a common occurrence, making it crucial for a support and ground motion analysis to be completed. Using data collected from seismometers previously placed on the moon, ground motion was applied to the finite element model of the structure. Mode shapes and frequencies were determined. Displacements and stresses developed, considering the structure having pin and clamped base supports, for both the thermal analysis and ground/support motion analysis have been compared. This study provides an affective methodology to determine the effect of the lunar temperature and support and ground conditions on the tall solar power structure. This will help lead to a more efficient and safe design of the structure that will function in an ideal manner; allowing for new possibilities and advancements in lunar exploration.

Keywords: Lunar Extreme Daily Temperature
Lunar Ground Motion
Lunar Structures
Structures on the Moon
Thermal Analysis
Ground/Support Motion Analysis

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Thursday April 18, 2024: Morning Session

<u>Session Title:</u> Modeling Methods for Regolith

<u>Session Co-chairs:</u> Patrick Harkness, Ph.D. (University of Glasgow, Scottland, GB) and Robert Anderson (NASA Jet Propulsion Laboratory, Pasadena, CA)
Room 124

10:20 AM **240 - *Discrete Element Modeling of LHS-1 Lunar Highlands Simulant and the Cone Penetrometer-Regolith Interactions***

Jesus Badal - Glenn Department of Civil Engineering, Clemson University, Qiushi Chen - Glenn Department of Civil Engineering, Clemson University, Liang Zhang - Department of Civil and Architectural Engineering and Construction Management, University of Cincinnati, Lei Wang - Department of Civil and Architectural Engineering and Construction Management, University of Cincinnati

<u>Abstract:</u> Resource acquisition on the Moon will require the development of in situ characterization, extraction, and collection methods. To accomplish this, a fundamental understanding of tool-regolith reactions is needed. Due to the inaccessibility of sites on the Moon, standard field tests to determine regolith strength under lunar conditions cannot be conducted. In this paper, the 2D discrete element method (DEM) is used to model and investigate cone penetrometer-lunar regolith interaction in a simulated lunar environment. The DEM model parameters are calibrated to Lunar Highlands Simulant (LHS-1) using biaxial test data and the Taguchi method. The DEM penetration tests assess the changes in the mechanical properties of the lunar regolith simulant in relation to penetration depth and a parametric study determined that there is a correlation between the size of the cone tip angle and the magnitude of the reaction forces during the penetration process into lunar regolith.

<u>Keywords:</u> In situ resource utilization
Discrete element method
Lunar Highlands simulant
Cone penetrometer

10:40 AM **9784 - Wear Testing and Modeling of Tools Interacting With Icy Granular Soil**

Zamir Syed - Singularity Solutions, Mehari Tekeste - Iowa State University, Paul Schafbuch - Iowa State University

<u>Abstract:</u> Lunar regolith is abrasive and damages machine elements that interact with it. Icy regolith in permanently shadowed lunar craters has been selected as a target for excavation to support in-situ resource utilization (ISRU) for the Artemis missions. A robust understanding of machine wear when interacting with icy regolith is needed to ensure successful ISRU.
A wear test apparatus was designed and fabricated to measure mechanical wear on tools and machines used to excavate and interface with icy regolith. The wear test apparatus was based on

the established pin-on-disc tester described in ASTM G99 with added novel features to maintain cryogenic regolith temperatures and evacuate excavated material.
Tool wear of an AISI 316L stainless steel pin was tested against two compositions of icy granular soil. The mechanics of icy granular soil cutting and excavating were also elucidated by examination of the post-test sand specimens. Possible abrasion mechanisms were also analyzed. Further effort is called for to develop models that can accept limited test data and predict durable tool life in general excavation processes.

Keywords: icy regolith
wear
DEM
discrete element method
ASTM G99
excavation

11:00 AM **1295 - ISRU Pilot Excavator (IPEx): Lunar Excavation Simulation Partnership with Caterpillar**

Jason Schuler - NASA, Eric Reiners - Caterpillar Inc., Kurt Leucht - NASA, Liz Zhang - NASA

Abstract: NASA's Space Technology Mission Directorate (STMD) is funding the development of a robotic excavator called the "ISRU Pilot Excavator (IPEx)" which will be a technology demonstration of excavating and transporting 10 metric tons of lunar regolith on the surface of the moon with a 30kg-class robotic excavator. IPEx will be the next generation of robotic excavators to use bucket drums as excavation tools. This is an evolution of the Regolith Advanced Surface Systems Operations Robot (RASSOR) developed at NASA's Kennedy Space Center.
One of the challenges facing lunar excavators such as IPEx is predicting the performance of the system and tuning its responses for operation in an environment with 1/6th Earth gravity and largely unknown geotechnical properties. Laboratory and field tests can help provide some data but it can be difficult and costly to reproduce the gravity conditions and various geotechnical configurations in a repeatable manner. To address this concern, NASA and Caterpillar Inc. have partnered to establish a simulation utilizing proprietary CAT discreet element modeling and multi-body dynamics software known as "Rocks3D" and "Dynasty" that can accurately predict the forces and vehicle reactions of IPEx under lunar environmental conditions.
This paper will discuss the first phase of this effort in which laboratory test data from RASSOR and individual experiments with BP-1 lunar regolith simulant were recreated in Rocks3D and Dynasty. These tests include single bucket drum excavation and wheeled mobility experiments. The paper will discuss the results of the simulation efforts and their ability to accurately reproduce the lab experiments, as well as next steps for combining these simulations to model the IPEx operations, and an opportunity for a future university challenge.

Keywords: RASSOR
Excavation
ISRU
IPEx
Simulation
DEM
Autonomy

11:20 AM **1131 - Evaluating the capability of the SPARTA toolkit to quantitatively characterize planetry regolith**

Robert Anderson - Jet Propulsion Laboratory/California Institute of Technology, Danielle Wyrick - Southwest Research Institute, Debra Buczkowski - John Hopkins University / Applied Physics

Laboratory, Jared Long-Fox - University of Central Flordia, Luke Sollitt - NASA Ames Research, James Dohm - Exploration Institute, Keith Chin - Jet Propulsion Laboratory/California Institute of Technology, Kris Zacny - Honeybee Robotics

Abstract: NASA's planetary exploration enterprise depends on a thorough understanding of planetary regolith's near-surface environmental and geomechanical properties. Understanding the regolith properties can shed light on several important scientific questions, such as how a planetary surface evolved over time, how water is delivered and distributed within the inner solar system, and how the regolith temperature changes within the diurnal cycle. Understanding regolith geomechanical properties is also crucial for the success of future planetary missions. In the past, a lack of knowledge about regolith properties has caused severe problems during mission operations. Recently identified interactions between landed subsurface probes and planetary regolith have revealed interesting, unexplained phenomena because of more complex surface environments than anticipated. The lack of understanding of regolith properties poses risks for many planned planetary missions or in situ resource prospecting. For its ease of integration with any landed missions, the SPARTA (Soil Properties Assessment Resistance and Thermal Analysis) toolkit will provide the much-needed knowledge of lunar regolith geomechanical and environmental properties and thus contribute to mission success.
The miniaturized SPARTA toolkit encompasses four terrestrial regolith-testing instruments, a Thermal Conductivity Probe (TCP), a Vane Shear Tester (VST), a Cone Penetration Tester (CPT), and a Dielectric Spectroscopy Probe (DSP), packaged for future surface landing missions. Three major objectives regarding science return, environmental information, and geomechanical properties can be achieved through the SPARTA toolkit. First, SPARTA will deploy a Thermal Conductivity Probe (TCP) to assess the thermal properties of the regolith, including temperature, thermal conductivity, thermal diffusivity, and thermal history. Second, it will use two instruments, the Vane Shear Tester (VST) and the Cone Penetration Tester (CPT), to evaluate the mechanical properties of the lunar near-surface regolith, including soil shear strength, cohesion, angle of internal friction, compaction, relative density, and pore size distribution. Finally, it will utilize the Dielectric Spectroscopy Probe (DSP) to identify water (<0.5%) and determine its form, whether water-ice or hydrated mineral. These measurements are critical for future planetary exploration and habitation, including rover trafficability and future construction.

Keywords: SPARTA
geomechanics
planetary regolith

11:40 AM **1839 - Micromorphic Continuum Models derived from Granular Micromechanics**

Anil Misra - University of Kansas

Abstract: For many problems in science and engineering, it is necessary to describe the emerging macro-scale behavior of materials formed of a very large number of grains by accounting for the micro-scale phenomena. Such materials are ubiquitous and impact diverse areas of engineering and science ranging from material development to biomaterials to geophysics. For such problems, continuum models are a preferred approach. Classical continuum theory is unable to take into account the effects of complex kinematics and distribution of elastic energy in internal deformation modes within the continuum material point. Therefore, there is a need for microstructure informed continuum models accounting properly for the deformation mechanisms identifiable at the micro-scale. Thus, mathematical description of their mechanical response must begin from the conception of grain-interactions. From this point of departure, either discrete or continuum descriptions can be elaborated. The question remains though how these materials with complex micro-structures and grain-interactions be analyzed efficiently? Even more

importantly, how their granular structure and grain-scale mechanics be predefined to produce predictable material behavior?

With the aid of examples drawn from discrete simulations and continuum models, and novel grain-scale experimental measurements, this presentation will show why/where traditional approaches are not successful and challenge us to seek innovations. The presentation will emphasize simplicity over complexity and primarily follow energy and variational methods to deduce tractable and plausible models and explanations. More than 2 decade old measured kinematics (displacements and rotations) in disk assemblies [1] and new experiments with controlled grain interactions [2], will be utilized as basis to motivate the granular micromechanics approach (GMA). This approach provides a paradigm that bridges the discrete models to appropriate continuum model, and obviates the need for extensive mechano-morphological parameters required for discrete models. Through GMA, micromorphic continuum model connected to the grain-scale can be deduced [3-5], which show on one hand the type of information lost, and on the other, the advantages gained when adopting this type of continuum model. The obtained model provides interesting predictions for granular media. These include wave dispersions and frequency band gaps [6-7], chirality and negative Poisson's ratio [2,8], and mesh independent damage localization [9].

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Keywords: granular micromechanics
continuum modelling
damage and plasticity

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April 15 - 18, 2024; Greater Miami, FL

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Thursday April 18, 2024: Morning Session

<u>Session Title:</u> Mission Concepts:
Resource Prospecting, Instruments and Enabling Technologies
<u>Session Co-chairs:</u> Ramiro Besada (Burns & McDonnell, Kansas City, MO) and Jeffrey Hopkins (Serenity Space Technologies, Pittsburgh, PA)
Room 114

10:20 AM **2370 - *Top-down, bottom-up: exploring science traceability matrix models for human exploration of planetary surfaces***

Ryan Ewing - Texas A&M University, Cherie Achilles - NASA, Maria Banks - NASA, Jared Broddrick - NASA, David Charney - NASA JSC Jacobs, Brett Denevi - Johns Hopkins Applied Physics Lab, Lauren Edgar - USGS, Ben Feist - NASA, Brent Garry - NASA, Alex Huff - Arizona State University, Jose Hurtado - University of Texas at El Paso, Nina Lanza - Los Alamos National Laboratory, Matthew Miller - NASA, Zachary Morse - NASA, Jacob Richardson - NASA, James Skinner - USGS, Chelsea Trainor - NASA, Catherine Weitz - Planetary Science Institute, Kelsey Young - NASA

<u>Abstract:</u> The Science Traceability Matrix (STM) is a core tool for space exploration missions. The STM guides measurements and actions needed to achieve the overarching science goals and objectives and acts as an anchoring document throughout the mission. Used widely on orbital, lander, and rover missions, little experience exists using an STM to guide human surface operations. Here, we report on experience developing and executing STMs from the NASA Joint EVA and Human Surface Mobility Test Team (JETT5) operation, which develops, integrates, and executes integrated human-in-the-loop tests and analogs to prepare for Artemis missions. The JETT5 Science Team was given primary and secondary "landing" sites in the San Francisco Volcanic Field of north-central Arizona and a database of images, elevation models, radar data, and derived data products (including slope and sun angle) all degraded to resolutions consistent with lunar orbital data. Detailed, published geologic maps, publications, and other resources were excluded from the database to emulate knowns/unknowns of a lunar simulation. STMs were developed using these images, a geological map created by the team based on surface expression in optical, radar, and topographic data, and baseline knowledge of the regional geology and terrain.

Two STM models were proposed for the primary and secondary "landing" sites – a "top-down" region-to-sites and a "bottom-up" sites-to-region. The top-down model developed science goals that fell into traditional geological topics that applied across both primary and secondary sites. The goals included surface geomorphic and sedimentary processes, regional volcanic processes, cross-cutting relationships, and volatile materials. The bottom-up model developed goals based on processes that cross-cut traditional geological disciplinary boundaries. The goals included assessing depositional processes, assessing tectonic and erosional processes, and assessing cross-cutting relationships and sequence of events.

Advantages of the top-down model included familiarity with and expertise within traditional geological disciplines and ease of parsing objectives and investigations based on these boundaries. However, bias exists because this model requires creating the STM with inherent interpretations that specific geological processes had occurred at the site. For example, the team had no prior

knowledge that fluvial or volcanic processes existed at the site, but inferred these processes based on image data provided. Advantages of the bottom-up approach included development of interpretation-agnostic, site-specific objectives with testable hypotheses embedded into the proposed investigations. Disadvantages included inability to trace from broad administrative-scale strategic goals (e.g., NASA Strategic Objective 1.2: Understand the Sun, solar system, and universe) and lack of familiarity with this novel approach. The top-down model was selected as the primary model and hybridized with the bottom-up model to include detailed investigations and hypotheses that applied to both sites.
Throughout the JETT5 planning process, the STM has served as an essential guiding document that includes traceability down to specific crew actions and prioritization of the actions. Initial tests indicate that the STM is used actively during the execution phase of exploration and critical for real-time decision-making during operations. The STM also serves as an anchoring, mission-wide agreed upon document to communicate the importance of science objectives to the flight control team.

Keywords: operations
science
concepts

10:40 AM **5340 - Inflatable reflectors for multiple human space exploration application**

Thomas Lagarde - Space Architecture Technical committe, Vincent Alder - Mars Real, Marc Cohen - Marc M. Cohen, Architect

Abstract: Study of a flexible and multi-purpose system consisting of wide circular inflatable reflectors that can have both their direction and degree of concave / convex nature finely adjusted. One or more reflectors can be used to concentrate solar energy to provide heat and light for photosynthesis. Provide energy for sintering regolith or even carve subterranean habitats with minimal mechanical aid. This system can avoid the considerable wear and tear normally associated with that kind of operation. Investigation of the thermodynamics of a subterranean habitat carved out and heated by reflectors. Improvement of mission robustness should any hardware fail with considerable thermal energy stored in the rock surrounding the habitat.
Living conditions can also be considerably improved, being warmer, brighter and greener than conventional habitats, with plenty of fresh food and air via photosynthesis.
There are still a lot of challenges facing the system such as micrometeorites, abrasive dust, cleaning and placement, though the advantages such as significant mission cost reduction, increased mission robustness and longevity far outweigh the challenges.
This paper will describe the concept of operations of the system such as but not limited to, the position and orientation of the reflectors and the duration of operations. Multiple trade-studies will also be presented to compare this approach to more traditional means of heating and building habitats.

Keywords: Direct Solar
Habitat
Plant
Power
Photochemical
Heating
Sintering
Human Exploration
Inflatable structure

11:00 AM **7121 - Mineralogical, Elemental, and Tomographic Reconnaissance Investigation for CLPS (METRIC): A Payload Designed for Exploration of Terrestrial Planetary Bodies**

Elizabeth Rampe - NASA Johnson Space Center, Philippe Sarrazin - eXaminart LLC, David Blake - NASA Ames Research Center, Paul Lucey - University of Hawaii at Manoa, Dean Bergman - Honeybee Robotics, Rachel Obbard - Dartmouth College and SETI Institute, Albert Yen - Jet Propulsion Laboratory, Christopher Haberle - Northern Arizona University, Kevin Cannon - Colorado School of Mines, Joseph Hamilton - NASA Johnson Space Center, Ryan Ewing - Texas A&M University

Abstract: Geological materials (indeed, all solid objects) are characterized by their crystal structure, elemental composition, and morphology. The Mineralogical, Elemental, and Tomographic Reconnaissance Investigation for CLPS (METRIC) instrument suite quantifies all three. These measurements address fundamental science questions (e.g., the origin and evolution of planetary bodies) and support the human exploration of space (e.g., the characterization of regolith for ISRU and the constraint of its geotechnical properties). METRIC comprises an X-ray Diffraction/X-ray Fluorescence instrument (XRD: mineral structure and XRF: elemental composition), an X-ray micro-Computed Tomography instrument (XCT: 3D internal micromorphology), and a hyperspectral imaging infrared spectrometer (IRS) to provide local/regional mineralogic context for these measurements. METRIC XRD/F draws heritage from the highly successful Mars Science Laboratory CheMin instrument. The METRIC XRD/F employs two separate sample cells, one optimized for XRD and one for XRF, resulting in more rapid XRD analysis (tens of minutes vs. tens of hours for CheMin) and an orders-of-magnitude improvement in XRF detection. XCT has not been deployed in space, so the METRIC XCT represents a new capability for solar system exploration. The XCT uses the same basic high-TRL components as METRIC XRD/F, decreasing its development cost for flight. The METRIC IRS is a derivative of the NASA Earth Science Technology Office funded Hyperspectral Thermal Imager instrument and utilizes the NASA Technology Transfer Program to incorporate a commercial-of-the-shelf infrared camera ruggedized for space by NASA Marshall Space Flight Center. The IRS spectral range (8–14 µm) and resolution (10.8 cm-1) are tailored to quantify mineralogy in rocks using their characteristic Reststrahlen bands and to characterize mineralogy of soils using the position of the Christensen Feature.

The METRIC payload is currently designed for deployment to the Moon on a Commercial Lunar Payload Services (CLPS) mission, where the XRD/F and XCT would be located on a lander and the IRS would be on deployed on a companion rover to evaluate the mineralogical diversity of the landing site. A pneumatic drill designed by Honeybee Robotics would excavate regolith up to 50 cm below the lander and deliver multiple aliquots of regolith to the XRD/F and XCT. The METRIC payload could also be deployed on a rover. In this case, a sample handling system on a robotic arm could scoop regolith and/or drill rocks and deliver powder to the XRD/F and XCT located in the rover's interior. Alternatively, METRIC instruments could be used singly or in combination on human space missions. The XRD/F and XCT could be used to characterize samples in a rover or in a science laboratory within a habitat. These data could help astronauts identify resource-enriched rocks and regolith and triage geologic samples to return samples of high interest for analysis in terrestrial laboratories. The IRS could be attached to a human-navigated rover to collect mineralogical data along a traverse and identify high-priority science samples.

Keywords: X-ray diffraction
X-ray fluorescence
X-ray computed tomography

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Thursday April 18, 2024: Morning Session

Session Title: Architected Materials for Terrestrial and Extraterrestrial Structural Applications
Session Co-chairs: Yunlan "Emma" Zhang, Ph.D (The University of Texas at Austin, TX) and Justin Littell, Ph.D. (NASA Langley Research Center, Hampton, VA)
Room 126

10:20 AM **5869 - *Architected Material Analogs of Shape Memory Alloys***

Yunlan Zhang - University of Texas at Austin, Pablo Zavattieri - Purdue University, Nilesh Mankame - General Motors

Abstract: Architected materials are a class of emerging materials usually consisting of numerous unit cells. By tailoring the geometry and topology of the unit cells, these materials can exhibit novel and/or customized properties and responses to physical stimuli. Here, we create a type of architected material that can reproduce the novel properties of shape memory alloys (SMAs) which are referred to as Architected Material Analogs of SMAs (ASMAs). ASMAs comprise periodic multistable unit cells and can exhibit both the salient behaviors, superelasticity, and shape memory effect of SMAs. ASMAs can be made from a wide variety of lightweight polymers, made by many different production processes as well as 3D printing and laser cutting, and are designed to respond to various stimuli such as heat, magnetic fields, and solvent absorption. ASMAs offer an alternative to expanding the design space for SMA-like material behavior, including larger-scale (e.g., space debris shielding structure) or applications (e.g., impact protective device).

Keywords: Architected Materials
Reversible Energy Dissipation
Shape Memory Behavior

10:40 AM **5960 - Design of in-space manufacturable spacecraft incorporating metamaterial technologies**

Othman Oudghiri-Idrissi - University of Michigan Ann Arbor, Avinkrishnan Vijayachandran - University of Michigan Ann Arbor, James McInerney - University of Michigan Ann Arbor, Wei-Chun Lu - University of Michigan Ann Arbor, Karina Heye-Smith - University of Michigan Ann Arbor, Andrea Poli - University of Michigan Ann Arbor, Ellen Arruda - University of Michigan Ann Arbor, Xiamoing Mao - University of Michigan Ann Arbor, Anthony Waas - University of Michigan Ann Arbor, Serife Tol - University of Michigan Ann Arbor

Abstract: This work presents novel design concepts of in-space manufacturable spacecraft that break free from the limitations of conventional launch loads and deployability. The spacecraft is designed to be mass-efficient, stable, and resilient with high precision. To this end, different metamaterial concepts are utilized to enhance stiffness, structural damping, and robustness to fracture of the spacecraft by developing and integrating dissipative, auxetic, and thermal metamaterials, and novel concepts such as plate stiffening via creasing. In effect, we numerically and experimentally demonstrate that creasing of a flat plate, either in the ordered or unordered

optimized manner, considerably increases its stiffness with a minimal mass cost and consequently enhances the precision of the host spacecraft. Further, we experimentally design, optimize, and validate mass-efficient and highly stiff dissipative metamaterial structural elements (beams, plates, joints) that make use of viscoelastic materials to induce and enhance structural damping. In fact, we prove that an "informed" and efficient introduction of viscoelastic materials in the metamaterial structural elements results in superior simultaneous (spatiotemporal) damping and stiffness properties, unlike conventional materials. Additionally, we also explore and characterize the mechanical properties of different combinations of printable and/or space-grade materials to achieve the desired optimal metaproperties. In the first part of our work, we integrate the different metamaterial technological solutions into the design of a large 1MW solar array made of a creased plate that is supported via a lightweight truss. The creased plate supports the solar cell arrays and is stabilized thanks to viscoelastic strips along the valley "creases" of the plate. The truss is made of the developed viscoelastic metamaterial beams, which contribute to the structural damping. The solar array design is numerically optimized by varying its geometrical and material parameters in a mass-stiffness-damping metric space and assessed in terms of structural integrity and post-damage precision under space-level accelerations. For experimental validation proposes, (numerical) scaling analysis of the optimal solar array design is conducted to identify the corresponding geometrical and material scaling laws. Finally, a lab-scale mock-up of the solar array design is fabricated and validated via static and dynamic (experimental modal analysis) experiments in ambient air and vacuum. The experiments are proved to validate their corresponding numerical models and, therefore, the full-scale model via the established scaling laws. Hence, it is concluded that high mass efficiency, stiffness, damping, and precision are achievable with the proposed design of the 3D-printable solar array. In the second part of the work, we design a lightweight, high-precision radiofrequency (RF) antenna that integrates auxetic metamaterial shells to mitigate the "pillowing effect" for curved reflective membranes and negative/ zero thermal expansion metamaterials to enhance the precision of the structure with space-level thermal loading (full sun and eclipse cycles). The design of the RF antenna is scaled down, prototyped, and tested in a thermal vacuum chamber to validate the function of the metamaterial technologies as well as the design metrics. It is also envisioned that the developed metamaterial technologies can serve for the design of spacecraft that require higher precision and resiliency, such as optical systems.

Keywords: In-space manufacturing
Space solar array
Space radiofrequency antenna
Viscoelastic metamaterials
Auxetic metamaterials
ZTE metamaterials
High precision

11:00 AM **4838 - Advancing 3D Concrete Printing for Extreme Environments: A Focus on Alaska**

Gonçalo Marques Duarte - The Pennsylvania State University/X-Hab3D, Jose Pinto Duarte - The Pennsylvania State University/X-Hab3D, Nate Watson - X-Hab3D, Sven Bilen - The Pennsylvania State University/X-Hab3D, Shadi Nazarian - The Pennsylvania State University/X-Hab3D, Aleksandra Radlińska - The Pennsylvania State University

Abstract: 3D concrete printing (3DCP) holds immense promise in addressing the global shortage of affordable housing and facilitating construction in extreme environments, both on Earth and beyond. Alaska, renowned for its challenging terrestrial conditions, serves as an ideal testing ground to push the boundaries of this technology. This work introduces and explores the design considerations for 3DCP construction in the extreme Alaskan environment, supported by a comprehensive design platform. The platform incorporates modules for generation, slicing, simulation, optimization, and construction simulation, seamlessly integrated into the Rhino and Grasshopper software. To validate the design solutions, a wall and an enclosure solution were fabricated, taking into account the unique challenges posed by Alaska. This work verifies the effectiveness of these design solutions and delves into the key challenges and benefits associated with employing 3DCP in construction under extreme conditions.

Keywords: 3D Concrete Printing (3DCP)
additive manufacturing/construction (3D printing)
structures and materials for extreme environments
terrestrial extreme environments – design and construction
computational design optimization

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Thursday April 18, 2024: Morning Session

<u>Session Title:</u> **Building Information Modeling (BIM): digital representation of physical and functional characteristics of space facilities**
<u>Session Co-chairs:</u> Luis M. Moreschi, PhD, PE (Bechtel Corporation, Reston, VA) and
Timo Hartmann, Ph.D. (Technische Universitat Berlin, Germany).
Room 117

10:20 AM **138 - *Bare basing on the Moon and Mars: How to utilize emerging Artificial Intelligence (AI) and Building Information Modeling (BIM) to Optimize Construction Planning for Future Lunar Habitats.***

John Borland - Texas A&M University, Patrick Suermann - Texas A&M University

<u>Abstract:</u> The logistical limitations associated with construction in austere environments necessitate advance planning techniques to ensure we optimize load plans and in situ sources of material utilization. Artificial intelligence (AI) is already revolutionizing the construction design process in terrestrial projects, bringing efficiency, precision, and innovation to the industry with early tools boasting 10-15% total construction cost savings. Our article proposes highlighting how AI use in construction design for bare basing on the Moon and Mars will modernize space engineers' business practices to ensure every aspect of the plan is optimized:

- AI tools reduce architect and engineer labor hours by 10-30% through design concept generation via analysis of vast data, previous projects, environmental factors, and user preferences. These algorithms suggest optimization solutions meeting specific design criteria like cost, sustainability, and structural integrity.
- AI enhances the design review process by automatically detecting potential clashes or errors in building plans by identifying issues before construction begins. This reduces budgets and timeline deviations 10-20% by preventing costly rework.
- AI streamlines the procurement and supply chain management process by analyzing historical data, market trends, and project requirements. This enables effective resource allocation, cost estimation, and risk management.
- AI empowers construction site monitoring and safety. BIM-based fall hazard identification and prevention with computer vision and image recognition technologies, detects hazards, wearables monitor worker activities, and ensure compliance with safety regulations.

Lastly, being able to create a digital representation of the space facilities will allow engineers to ensure the physical and functional characteristics of the facilities before the first rocket blasts off. Such BIM software helps in understanding the layout, equipment needed to construct, and any other unique characteristic one may encounter in these environments.

<u>Keywords:</u> Artificial Intelligence
AI
Machine Learning
Building Information Modeling
BIM

10:40 AM **4178 - An information model for representing fault-symptom relationships in Temperature and Humidity Control Systems (THCS)**

Min Young Hwang - Carnegie Mellon University, Burcu Akinci - Carnegie Mellon University, Mario Bergés - Carnegie Mellon University

Abstract: Current fault diagnosis methods for Temperature and Humidity Control Systems (THCS) are developed under the assumption that the system configuration will remain unchanged throughout its lifetime. However, during the operation and maintenance phase of a habitat's life, the system configuration can undergo changes. These changes include component replacements with higher-performing ones, interaction between subsystems, and reconfiguration of the habitat leading to the collaboration of different systems. The International Space Station (ISS) has encountered such changes, including component replacements, THCS support to the Electrical Power System (EPS), and the docking of visiting vehicles that provide supplementary THCS capabilities. Existing fault diagnosis methods require experts to remodel the system or retrain the classification function in order to update the fault-symptom relationships. Failure to reflect the changes in the system configuration may result in inaccurate fault diagnosis based on the established fault-symptom relationships. As we venture beyond the Lower Earth Orbit (LEO), communication delays increase, necessitating Earth-independent operations within the habitat. Therefore, accurate onboard fault diagnosis is crucial and replacements for the constant troubleshooting process with mission control for the ISS must be researched. This paper is part of a series of efforts to automatically integrate system configuration changes into fault diagnosis methods. This adaptability enables the system to diagnose and recognize previously unseen fault patterns, generating relevant fault-symptom relationships for new situations without manual intervention. The first step in revising the fault-symptom relationships is to identify the existing ones based on the assumed configuration. However, currently, there is no generic and extensible information model available to represent fault-symptom relationships before and after the revision process.
To address this gap, we present the motivation to represent fault-symptom relationships by illustrating their changes during system reconfiguration. We survey existing efforts in the representation of fault-symptom relationships within the aerospace sector (e.g., Fault Trees, Failure Modes and Effects Analysis Tables, D-matrices) and related fields. Furthermore, we extend the existing terrestrial THCS analog information model called Brick and incorporate the representation of fault-symptom relationships. We implement the extended information model using (i) one of the case study scenarios, (ii) fault-symptom relationships from the Carnegie Mellon University Building Automation System (a terrestrial THCS analog), and (iii) Failure Modes and Effects Analysis tables according to MIL-STD-1629A (Notice 2), currently employed for the ISS, to evaluate the applicability and breadth of the model.

Keywords: fault diagnosis
semantic information models
ontology
Temperature and Humidity Control Systems

11:00 AM **9216 - BIM Uses for the Automation of Construction and Operation of Outer-planet Facilities**

Bita Astaneh Asl - California State University, East Bay

Abstract: The construction of outer-planet facilities necessitates exploring and implementing new technologies that can overcome the unique challenges of extraterrestrial environments. Construction automation can bring numerous benefits to these projects, including reduced reliance on human labor, increased efficiency, enhanced precision, and improved safety, requiring

multidisciplinary collaboration among Architects, Engineering, Constructors, and owners (AECO). Building Information Modeling (BIM) serves as a shared knowledge resource for all AECO project stakeholders that allows for collaboration, coordination, and integration of information across disciplines and throughout the entire lifecycle of a project, from design and construction to operation. There are twenty-three BIM uses defined throughout the lifecycle of a facility. These BIM uses can support construction automation. This presentation discusses the BIM uses utilized for pre-construction and construction by contractors and the operation of the facilities by the owners, focusing on considerations for outer-planet facilities and the technologies that need to be integrated with BIM for automating the process.

In automated construction, robots need to know the exact location of the components in the facility and in correlation to the site to build and operate. While local coordinates captured by traditional surveying methods can provide useful data, in outer-planet conditions, a global coordinate provided by Geographic Information Systems (GIS) is a well-suited way to define the coordinates that can be used by GPS-equipped robots on the planet's surface as well as spacecraft. When GIS is integrated with BIM, robots find the exact location of components that need to be installed or need maintenance. The real-time data collected by robots, which technologies like laser scanning can do, can be fed into GIS platforms and compared to BIM for evaluating construction progress to detect potential errors or deterioration from as-built conditions. An artificially intelligent robot can facilitate this process as it allows the robot to make decisions and fix construction errors or do corrective maintenance without human intervention.

In terms of BIM uses, a BIM/GIS integration tool can be used to support the site selection. Then with 3D laser scanning, the captured point cloud data can be imported into the BIM tool to define the existing conditions. The contractor can use the model-based cost estimation to support the design team during design. To create a precise model ready for execution by robots, the model needs to be reviewed and coordinated to ensure that it has no design errors and that the facility systems do not collide. The contractor can use the model for the site logistics plan, work layout, and 4D modeling to specify the permanent and temporary facilities and define the sequence of construction to be provided as input to robots to build based upon them under the supervision of the contractors. A Record BIM can then be prepared to be used by the owner for operation and maintenance. NASA requires a Record BIM created based on the as-built conditions with a level of development (LOD) of 500 for its facilities. The Record BIM, combined with sensors, performance simulations, and GIS, forms the digital twin that can allow robots to operate and maintain the facility under the supervision of facility managers.

Keywords: Outer-Planet Construction
BIM
Construction Automation
Robot
GIS

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Thursday April 18, 2024: Morning Session

<u>Session Title:</u> 3D Printing Applications for Lunar and Martian Construction
<u>Session Co-chairs:</u> Nathan Gelino (NASA Kennedy Space Center, FL) and Seung Jae Lee, Ph.D. (Florida International University, Miami, FL)
Room 115

10:20 AM **3666 - *Are 3D Printers Universal Constructors?***
Alex Ellery - Carleton University

<u>Abstract:</u> In-situ resource utilisation (ISRU) on the Moon has admitted a wide variety of approaches including the use of 3D printing of regolith. We take the view that a radical approach is required for full, low-cost yet sustainable lunar industrialisation. The key to this is the universal constructor, first conceptualised by John von Neumann as the basis of the self-replicating machine – a machine that can construct a copy of itself given the appropriate material feedstock, energy and instructions. We explore the concept that 3D printing may constitute a universal construction mechanism. The first step in demonstrating that 3D printing may constitute universal construction is the RepRap 3D printer, a fused deposition modelling (FDM) printer that could 3D print many of its own plastic parts, i.e. partial self-replication. FDM has been deployed in space but is restricted to 3D printing of polymers. A further step has been taken in demonstrating that a suite of 3D printing techniques may be employed to 3D print an electric motor, the basis of the kinematic machine, requiring extensive use of FDM-extruded metal-impregnated polymer. Metal 3D printing is well-established offering a variety of techniques but most are variations on three basic approaches: (i) selective laser sintering/melting (SLS/M) is the most popular approach to metal 3D printing but can potentially be adapted to polymer or ceramic 3D printing; (ii) electron beam additive manufacturing (EBAM) is restricted to metal 3D printing only; (iii) binder jetting (BJ) requires the adoption of polymer binders. EBAM is preferred over selective laser sintering because: (i) wire feed rather than powder bed eliminates levitated dust under microgravity conditions; (ii) electron beam generation is much more efficient than laser beam generation. We examine the implementation of EBAM for a variety of metal-based 3D printing. The paucity of carbon on the Moon ~102 ppm prevents extensive use of polymers locally rendering certain 3D printing techniques unviable on the Moon. We require substitution of plastic by non-metals that can be leveraged from lunar resources. This introduces considerable challenges for 3D printing, calling into question its suitability for universal construction. 3D printing non-metals is considerably more challenging than that of metals – such non-metals include refractory ceramics such as alumina, silica and glasses (such as basalt glass and fused silica glass). They involve considerably higher processing temperatures and/or the use of binders or matrix materials such clays or metals derivable from lunar resources. The Moon affords the possibility of selective solar sintering using Fresnel lens heat sources for 3D printing which we have been exploring. We shall examine these issues in detail. Although lunar ISRU has emphasised metal extraction, ceramics and glasses are crucial as multifunctional materials to complement metals as they are typically used in conjunction with them, e.g. metal electrical wiring requires electrical insulation.

Keywords: In-situ resource utilisation
3D printing
Universal constructor
Electron beam additive manufacturing
Selective solar sintering

10:40 AM **5052 - Economic Analysis of Practical Additively Manufactured Parts for use on the Lunar Surface.**

David Purcell - Colorado School of Mines, Christopher Dreyer - Colorado School of Mines

Abstract: As NASA readies to return to the Moon, mission planners and engineers have been tasked with developing the infrastructure required for a permanent foothold on the lunar surface. Among the first tasks of any such project, is identifying specific sectors such as construction, excavation, transportation, etc. which a lunar base will require for long term operations. Each of these sectors has their own subsets of requirements, supplies, and equipment which will be vital for proper operation. Initially, equipment will be supplied from Earth, via cargo delivery missions. As base maturity develops however, the related costs will quickly become untenable if no in-situ supply chain can be developed. Additive Manufacturing (AM), is a technology which can rapidly be leveraged in order for a long-term lunar base to become self-sustaining.

This study will provide three examples of components which could be produced with industrial scale AM through a lunar in-situ manufacturing pipeline. Manufacturing, transportation, and post processing costs will be identified before each AM produced part could be put into service. Throughout this study, "industrial scale" limits the build volume of applicable AM technologies to a maximum of two meters in length/width (X, Y), and two meters in height (Z). Additionally, each part will be analyzed in order to determine which type of AM technology is most suitable for manufacturing operations. Descriptions of each of the seven types of AM technology referenced for this study can be found in the ISO/ASTM 52900:2015 standard [1]. The final costs [2] and performance of AM produced parts will be contrasted against functionally identical components which have been manufactured with more traditional methods (casting, machining, die pressing, etc.). The components to be included in this study are: Bricks (pavers, tiles), anchors, and grousers. Grousers (also known as cleats, or lugs) are components used to increase traction and maneuverability of rover wheels, similar to the tread of a tire.

Each of these components has application in distinct, yet related sectors of lunar base operations. Bricks can be used in the construction [3] of habitats, berms, or roads. Grousers will be required for any wheeled vehicle traveling on the lunar surface and are likely to need replacement during the lifetime of the vehicle. Anchors will be used in construction applications such as landing pads, tension cables, or slope stabilization. This study will also incorporate technological improvements that will develop alongside base maturation. For example, initial AM produced parts may be manufactured on state of the art, terrestrially sourced AM machines. As technology improves, AM machines will eventually be built on the lunar surface and will produce parts using completely in-situ sourced feedstock, representing an independent manufacturing operation.

Though still a work-in-progress this study will present data on the three described AM components, illustrating the technological, and economic benefit of using specific AM produced parts on the lunar surface. Comparisons of AM processes will be detailed; in addition to the rationale for choosing to print these components in lieu of other manufacturing methods.

References:

[1] ISO/ASTM 52900:2015

[2] Thomas, Douglas S., and Stanley W. Gilbert. Costs and Cost Effectiveness of Additive Manufacturing. NIST SP 1176, National Institute of Standards and Technology, Dec. 2014, p. NIST SP 1176. DOI.org (Crossref), https://doi.org/10.6028/NIST.SP.1176.

[3] Farries, Kevin W., et al. "Sintered or Melted Regolith for Lunar Construction: State-of-the-Art Review and Future Research Directions." Construction and Building Materials, vol. 296, Aug. 2021, p. 123627. DOI.org (Crossref), https://doi.org/10.1016/j.conbuildmat.2021.123627.

Keywords: Additive Manufacturing
ISRU
Lunar Construction
Lunar Infrastructure
Economic Study
Bricks
Anchors
Grousers

11:00 AM **3568 - Strengthening and 3D Printing of Magnesium Silicate Hydrate (MSH) Binder for Martian Construction**

Shayan Gholami - Texas A&M University, Yong-Rak Kim - Texas A&M University, Faezeh Salehi - Texas A&M University

Abstract: Utilizing in-situ materials through automated 3D additive manufacturing is crucial for future space construction, particularly for Mars. In this study, we attempted to use magnesium silicate hydrate (MSH) binders as a promising option, as the Martian mineral resources are rich in silica and magnesium, and MSH exhibits a high reactivity with CO2, which can be benefitted from the Martian atmosphere consisting of a high concentration of CO2, differing from Earth. This study aims to examine the strengthening and 3D printing of MSH binders formulated using a Martian regolith simulant (MGS-1) as fine aggregates, light-burned magnesium oxide, micro silica, and water. To further investigate the effects of carbonation on physical-mechanical properties, two different CO2 curing regimes were considered: (1) incubator with 20% CO2 concentration and (2) ambient air. The experimental characterization included rheological, chemical, and mechanical analyses. The testing results revealed that CO2 curing enhanced the strength of MSH binders, implying the promising role of CO2 in the Martian atmosphere. Furthermore, the relationship between the MSH mixture design and 3D printability was investigated, and key parameters for the optimal composition for successful printing were explored. Results, although limited to drawing definite conclusions at this stage, imply the potential feasibility of in-situ resource utilization (ISRU)-based Martian construction.

Keywords: In-situ Resource Utilization (ISRU)
Martian construction
Magnesium Silicate Hydrate (MSH) binder
3D printing
Carbonation
Experimental characterization

11:20 AM **1342 - RENEST – Low Energy Additive Construction for the Moon and Mars**

Travis Vazansky - Astrobotic, Jon Slavik - Astrobotic, Connor Luken - Astrobotic

Abstract: 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 (Refurbishment Enhanced Non-sintered Extrudable Surface Technology), 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.

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.

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.

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.

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.

Keywords: Additive manufacturing
Landing pad
Construction
Plume-surface interactions

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Thursday April 18, 2024: Afternoon Session

Session Title: Rocket Exhaust Interactions with Regolith
Session Co-chairs: Christopher Dreyer, Ph.D. (Colorado School of Mines) and S. Joseph Antony, Ph.D. (University of Leeds, Leeds, UK)
Room 124

01:20 PM **800 - *Predictive Theory for Rocket Exhaust Eroding Soil***

Philip Metzger - UCF

Abstract: A new analysis of reduced gravity experiments has finally identified the remaining parts of the equation that can predict the blowing of soil during lunar landings. There was a mystery surrounding the fact that crater depth grew as the logarithm of time although the differential equation that produces that scaling implies that craters grow faster in volume as they become larger. It turns out this is correct and it provides deep insight into the nature of fluid-induced erosion. Larger craters grow faster because the larger surface area of the outer conical crater is avalanching into the inner crater where erosion occurs. This added mass loading into the gas does not provide any feedback that slows the erosion rate because mass loading is not a rate-limiting process. Instead, it is diffusion of energy through the laminar sublayer that controls erosion rate. Avalanching sand is already delivered above the laminar sublayer, so as the avalanching increases, total erosion also increases. Only the sand eroded in the inner crater where gas lifts soil through the laminar sublayer participates in the rate limiting process. Reduced gravity versions of these experiments have also shown that erosion rate is controlled by cohesive energy density of the soil and potential energy to lift the grains only one grain diameter. This tiny height is below the laminar sublayer, again confirming that energy diffusion below that height is the rate-limiting process. This indicates that molecular thermal velocity, which transports kinetic energy through the laminar sublayer, is crucial to the erosion scaling. This is the missing velocity that was discussed at the Earth & Space Conference 2010. The missing velocity now makes the equation complete. The equation has been tested against the optical density of blowing soil in Apollo landings and has found a perfect fit. The theory can for the first time calculate the total soil that was blown during the Apollo landings and can predict the amount blown in future landers. It turns out that in Apollo landings 12.8 times more soil was blown than previously believed, or 33 tons versus the prior estimate of 2.6 tons. This gigantic mass is spread over a 17 m radius and is only 7 cm deep at the deepest point, agreeing with post-landing observations of the soil. There is no data set that contradicts this finding of much more blown soil. The resulting damage to surrounding hardware should also be an order of magnitude larger than per previous estimates. These results have important implications for mitigating rocket blast effects on the Moon.

Keywords: Rocket exhaust effects
Lunar landings
Dust
Reduced Gravity
Regolith mechanics

01:40 PM **1515 - Direct Comparison of Mitigated and Unmitigated Plume Surface Interactions in a Drop Tower Vacuum Experiment**

Kayla Schang - University of Central Florida, Alexander Nicola - University of Central Florida, Helen Carson - Lunar PAD / Independent Researcher, Kaveon Smith - Georgia Institute of Technology, Alyssa Bulatek - University of Florida, Andres Campbell - Sierra Space

Abstract: Artemis-era plans for sustained human presence on the Moon will require the launch and powered descents of large vehicles within range of habitats, which represent significant hazard cases for unmitigated plume surface interactions (PSI). There are currently gaps in the understanding of the parameter space that surrounds these interactions, partly due to the limitations of current computational fluid dynamics (CFD) models and a corresponding lack of physical data to validate models. To address this, research has been previously conducted to 1) understand the physics of gas-granular interaction through a Gas-Regolith Interaction Testbed (GRIT) drop tower vacuum experiment and 2) develop and systematically study lunar landing pad geometries through the Lunar Plume Alleviation Device (Lunar PAD) project. Now, we begin to characterize the effect of landing pads on PSI through a direct comparison of unmitigated PSI and landing pad PSI testing in the same environment.

This study reports on modification of the GRIT experiment to accommodate a small 3D printed plastic landing pad model which demonstrates a first step towards characterizing the hazard reduction landing pads provide. Experiments were performed at the University of Central Florida Stephen W. Hawking Center for Microgravity Research, the same facility used for GRIT. Landing pad selection was based on previous Lunar PAD design iterations and intended to represent one of the simplest effective cases for a medium-sized lander. The nozzle height, pulse duration, and regolith simulant are selected to replicate reported GRIT setups for a direct comparison of the mitigated (with pad) versus unmitigated effects of the plume in this vacuum microgravity environment. Particle tracking equipment, plane lasers, and optical cameras were used for data collection.

By providing a direct comparison between no-landing-pad and landing-pad-present PSI scenarios, this study offers the first direct look at how current landing pad designs are performing in a relevant environment and demonstrates how landing pads can be effective PSI mitigation technologies. This experiment serves as a proof of concept for future exploration of the PSI and landing pad parameter space which would account for different landing profiles, h/De ratios, regolith-constructed landing pad design features, and/or regolith/surface characteristics. We learn that a better understanding of these parameter spaces is needed to have accurate CFD models which then can help efficiently design surface and landing infrastructure. As shown here, landing pad studies on natural and constructed surfaces are a viable method to obtain this information. Once we have this understanding, we can optimize landing pad features to further minimize the risks while meeting requirements for constructability and compatibility with the harsh lunar environment.

Keywords: plume surface interactions
vacuum
microgravity
drop tower
lunar landing
landing pads
regolith simulant
PSI
PSI mitigation
CFD
computational fluid dynamics

02:00 PM **1544 - A Hybrid CFD/Engineering Model Tool for Lunar Lander Surface Erosion Prediction**

Andrew Weaver - Jacobs Space Exploration Group, NASA MSFC, Thomas Shurtz - Jacobs Space Exploration Group, NASA MSFC, Peter Liever - Jacobs Space Exploration Group, NASA MSFC, Timothy Dawson - Jacobs Space Exploration Group, NASA MSFC, Jason Howison - Jacobs Space Exploration Group, NASA MSFC, Jeffrey West - NASA Marshall Space Flight Center

Abstract: Plume-Surface Interaction (PSI) between lander engine plumes and landing area regolith creates hazards in obscuration and contamination by particle clouds, high-energy ejecta debris streams, and landing area cratering damage. The PSI surface erosion effects range from onset of viscous shear driven surface erosion progressing to regolith bed fluidization and ultimately to diffused gas eruption with deep crater formation. During a powered landing on the Moon, the erosion that occurs for the early portion of the trajectory is within the Viscous Erosion (VE) regime. A rapid engineering simulation of the PSI induced erosion footprint and location of distinct crater formation provides cost-effective engineering insight to lander developers on the influence of the lander propulsion system configuration and descent path before PSI analysis progresses towards more complete and expensive full fidelity PSI physics simulations.

The NASA/MSFC Fluid Dynamics Branch (ER42) has constructed a hybrid CFD/Engineering-Model computational toolset of PSI driven lunar soil erosion, specifically formulated to apply in the viscous erosion regime. This model, Loci/Chem-DIGGEM, was calibrated/anchored against Apollo landing reconstructed surface erosion levels to establish a correlation model of the viscous erosion mass flux as a function of the plume flow induced surface shear stress. The Descent Interpolated Gas-Granular Erosion Model (DIGGEM) module predicts the surface erosion driven material removal as a function of the local surface shear stress distribution provided by the PSI CFD simulation. The original implementation of DIGGEM in 2022 featured a quasi-steady loosely coupled simulation procedure interpolating across distinct trajectory points. Recent development has advanced this capability to a transient, fully coupled, moving vehicle trajectory simulation capability. The resulting cumulative surface recession is modeled as a moving surface within the Loci/Chem CFD simulation to deliver the surface recession topology evolution over the lander descent trajectory. Verification/validation of this toolset is performed against predicting the erosion patterns observed for various Apollo landings.

This work supports development and assessment of a cascade of predictive simulation capability for PSI, ranging from CFD-informed engineering correlations, hybrid CFD-engineering model simulations, and two-way fully coupled Gas/Granular Flow Solvers using Eulerian-Eulerian CFD modeling. This cascade of tools allows applications suitable to different risk postures and different times in design and analysis cycles. The cascade of tools is currently being used for NASA Flight Programs such as Human Lander System (HLS) and Commercial Lunar Payload Services (CLPS), and PSI induced environments affecting Lunar Site Planning.

Keywords: Lunar Landing
Plume-Surface Interaction
Regolith Modeling
Plume Induced Erosion
Modeling and Simulation

02:20 PM **6846 - Understanding The Effect of Geotechnical Properties on Plume Surface Interactions**

Brandon Dotson - University of Central Florida, Aiden St. John - University of Central Florida, Dhaka Sapkota - University of Central Florida, Dan Britt - University of Central Florida, Philip Metzger - University of Central Florida

Abstract: As human and robotic space exploration missions strive to land larger payloads on the surfaces of planetary bodies, understanding the fundamental principles, relationships, and effects of Plume-Surface Interactions (PSI) is vital to mission success. With humans returning to the Moon under the Artemis program, understanding and mitigating PSI effects will also be essential for the protection of personnel and equipment on the Moon. To help characterize the underlying mechanics associated with viscous erosion and crater formation, experimental measurements using regolith simulants and subsonic, non-reacting flows were completed using compressed air in a split-plate cratering setup. More specifically, these investigations examined the underlying effects of particle size distribution, grading, compaction, atmospheric conditions, and exhaust flow characteristics on viscous erosion rates and crater formation using Lunar highlands simulant (LHS-1), Lunar mare simulant (LMS-1), and LHS-1D (Dust) Exolith simulants. Examining specific surface properties related to PSI, this research also incorporates a series of geotechnical measurements related to density, cohesion, shear strength, and porosity of relevant regolith simulants under atmospheric conditions while exposed to a non-reacting, laminar flow. Exhaust velocity profiles were directly measured using pitot-static devices as a function of exhaust height, and laminar flow was accomplished by adjusting upstream chamber pressures. For these plume tests, data was collected using video tracking of crater formation, and analyzed using image analysis techniques developed in Python. Compaction of the regolith simulants was varied using mechanical vibrations at 20-40 Hz, while particle shapes and size distributions were recorded using a Cilas-1190 laser-diffraction size analyzer. This study has also leveraged new techniques and processes to include mathematical characterizations of particle size distributions, LiDAR scanning of craters, and non-destructive density measurements using gamma-ray spectroscopy with radioactive Cesium-137. Ultimately, these techniques were used to document the effects of mass flow rate on viscous erosion and crater formation geometry with respect to exit nozzle velocity, height above the surface, compaction, and chamber pressure with laminar, subsonic flow in terrestrial atmosphere. Initial results show that sample density and surface compaction play in important role in both the shear strength and cohesion of a sample, as well as the resulting viscous erosion during PSI and crater formation. While PSI effects were still noted, increasing the bulk density and compaction of regolith simulant resulted in a decrease of viscous erosion. As robotic and human exploration of space continues, data collected from this research will help inform existing PSI computer models as well as future mission planning. Understanding PSI effects will also be important when planning for sample return or human missions to the asteroids, Mars, or the Martian moons.

Keywords: Plume Surface Interaction
Plume Effects
Regolith Simulants
Regolith
Geotechnical
Exhaust
Crater Formation

02:40 PM **7615 - Gas-granular mechanics observed in a subscale, reduced pressure plume-surface interaction test**

Kayla Schang - University of Central Florida

Abstract: Spacecraft landing retropropulsively cause plume-surface interactions (PSI) which can erode and mobilize regolith. This project is a case study in a new methodology applied to initial Physics-Focused Ground Test (PFGT) data in order to analyze crater profiles recovered from this subscale, inert-gas PSI vacuum test. It provides new terminology and proposes quantitative descriptors of crater behavior to allow for a statistical comparison between tests. These variables can also be tied to predictions of PSI behaviors, such as those described in the literature. We define crater profile features as roughness, crater profile shape, and transience, which proved to be valuable quantifiable descriptors that distinguish between different observed behaviors. Additionally, a case study demonstrates how these variables can be used to compare across tests, and as a methodology to provide insights into PSI behavior, such as a relationship between the creation of bimodal crater shapes in vacuum and either diffused gas eruption or viscous erosion.

Keywords: plume-surface interactions
granular mechanics
entry descent and landing

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Thursday April 18, 2024: Afternoon Session

Session Title: Ballistic Impact and Crashworthiness of Aerospace Structures
Session Co-chairs: Justin Littell, Ph.D. (NASA Langley Research Center, Hampton, VA) and Lucas Laughery, Ph.D. (ICON Technology Inc. Austin, TX)
Room 126

01:20 PM **8560 - *Impact-resistant Instability-based Architected Materials (IAMs) for Extraterrestrial Construction and Expeditionary***

Li Wan - Civil, Architectural and Environmental Engineering, University of Texas at Austin, Austin, 78712, USA, Sergio Diaz - Civil, Architectural and Environmental Engineering, University of Texas at Austin, Austin, 78712, USA, Yunlan Zhang - Civil, Architectural and Environmental Engineering, University of Texas at Austin, Austin, 78712, USA

Abstract: Architected materials are an emerging class of innovative materials that can be designed to exhibit extraordinary properties by leveraging constituent materials and topology. These materials can be designed to be ultra-stiff, ultra-lightweight, and even respond to external stimuli. One type of architected materials, Instability-based Architected Materials (IAMs), consists of building blocks exhibiting multistable geometric phase transformations. By tailoring geometry and topology, IAMs can enable large reversible deformations (on the order of 50%) while dissipating and absorbing energy beyond the capabilities of conventional materials. These exceptional mechanical properties are attractive for various engineering applications such as landing gear, tunable vibration isolation systems, and impact protective structures. Many studies have demonstrated that IAMs can dissipate energy under quasi-static uniaxial loading conditions, and most IAM designs focus on enabling such reversible energy dissipation capacity under a preferred loading direction. Furthermore, the mechanical behavior of IAMs was mostly tested under quasi-static loading conditions, even though loads are in arbitrary directions and dynamic in practice. This research aims to unveil new principles to facilitate the creation of IAMs with new geometry and topology that can leverage the geometric phase transformation at the unit cell level to resist complex and highly dynamic loadings such as impact and blast. Our approach imbues IAMs with the ability to be modified through the selection of constituent materials, unit cell geometry, and IAM topology to enhance the energy dissipation capacity along multiple loading directions. Both analytical and numerical (FEA) models are created to guide the design of IAMs. In addition, IAMs prototypes are fabricated through additive manufacturing and tested in a dynamic environment to understand the behavior of materials. The results of this study show the new IAMs exhibit higher performance in terms of specific energy dissipation capacity and the most robust response to loading direction among all the current designs. This approach can be applied to guide the development of resilient materials and structures for extraterrestrial construction and expeditionary.

Keywords: Architected Materials
Energy dissipation
Instability

01:40 PM **157 - Analysis of a Landing System for Planetary Payloads Utilizing Passive Energy Absorbing Composite Structure**

Jacob Putnam - NASA, Matlock Mennu - NASA, Justin Littell - NASA

Abstract: Delivery of a payload from space to a planetary surface currently requires the development of an application specific landing system to protect the payload from forces imparted during impact with the planet surface. Often, active energy attenuating systems such as retro-rockets, deployable parachutes, and airbags are utilized within these landing systems to reduce landing impact energy. Unfortunately, these active systems come at a cost; active energy attenuating systems are susceptible to system faults which may limit or completely negate their energy attenuating capability. Additionally, components needing to be stowed such as fuel, parachutes, and airbags increase design complexity, cost, and weight. To overcome these limitations, this study examines the potential of passive energy attenuation through energy absorbing structural design and composite materials to mitigate landing loads for small payload planetary delivery.

Researchers at the National Aeronautics and Space Administration (NASA) Langley Research Center (LaRC) have conducted extensive research into developing energy absorbing structures and components for the attenuation of impact energy under various loading conditions including aircraft crash and spacecraft impact. The current study leverages this research to design a lightweight planetary delivery system which utilizes unique outer mold line (OML) geometry and passive energy absorbing structural design to limit landing loads across potential planetary surface environments. The OML geometry is designed to control impact orientation and provide self-righting capabilities for slopped impact surfaces. The internal structure is composed of composite material structures arranged to provide energy absorption which is robust to impact angle and impact velocity.

The developed planetary delivery design concept will be evaluated using finite element (FE) model analysis. Simulations of landing impacts with representative soil surface environments will be used to characterize the energy absorbing capabilities of the landing system. Sensitivity of predicted impact force to landing environment, impact angle, and impact velocity will be assessed to identify capabilities and limitations of the initial structural design. Results will be used to determine the feasibility of a lightweight composite structure to passively absorb landing energy for robust planetary payload delivery.

Keywords: Planetary payload
Crashworthiness
Composite

02:00 PM **1759 - Trade Study of Impacting Resisting Structures on the Lunar Surface**

Arsalan Majlesi - The University of Texas at San Antonio, Amir Behjat - Purdue University, Adnan Shahriar - The University of Texas at San Antonio, David Avila - The University of Texas at San Antonio, Shirley Dyke - Purdue University, Julio Ramirez - Purdue University, Arturo Montoya - University of Texas at San Antonio

Abstract: The design of lunar habitats demands a non-traditional approach due to the constraints imposed by the extreme environment in deep space and the limited launch mass available for NASA missions. The potential damage caused by micrometeorite impacts, a natural hazard to lunar habitats, will generate high power demands to maintain stable thermal conditions within the habitat and require the allocation of dedicated resources for conducting repair actions. Locally available solidified regolith and high-strength and low-density transported materials represent two viable options for lunar habitat construction. This study assessed the performance of different structural configurations for a semi-spherical dome, which involved varying materials and thickness, by comparing the power consumption and the time required for repairs due to impact damage over a 20-year service period. The trade study was performed under the recently developed Control-oriented Dynamic Computational Modeling (CDCM) framework, a modular platform for modeling space habitats. To conduct this analysis, it was essential to quantify the perforation damage depth after every micrometeorite impact for regolith and aluminum targets. Hence, within the CDCM, a polynomial equation was utilized to predict the perforation depth of micrometeorite impacts with varying diameters and velocities. The study showed that if a regolith and aluminum habitat are constructed with the same equivalent mass and exposed to the same micrometeorite impact, the regolith habitat will experience a higher perforation depth than the aluminum habitat. This behavior led to higher repair time demands in regolith habitats. Moreover, regolith structures exhibited more significant performance uncertainty under micrometeorite impacts than aluminum structures with the same equivalent mass; however, they consume less power during their lifecycle. While the evaluation relies on the assumptions employed in regolith modeling, the study demonstrates that CDCM is an effective tool for assessing the potential performance of habitat designs over an extended operational lifespan

Keywords: trade study
regolith structures
metallic structures
meteorite damage
power consumption

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Thursday April 18, 2024: Afternoon Session

Session Title: Engineering Aspects for NASA's Moon to Mars Architecture and other International Programs

Session Co-chairs: Robert W. Moses, Ph.D. (Tamer Space, LLC, Richmond, VA) and Robert Mueller (NASA Kennedy Space Center, FL)
Room 117

01:20 PM **355 - *Base Planning from the Moon to Mars: Development Logics Informing a Morphological Approach to Surface Infrastructure***
Melodie Yashar - ICON Technology Inc

Abstract: In this presentation, we outline the need for Lunar base planning development logics enabling a morphological approach to infrastructure development and strategic expansion at key landing sites at the Lunar south pole. In contrast to historical examples of static or fixed Lunar master plans, our study initiates development logics for emerging morphologies of Lunar base planning. Parameters and requirements for the development logic include topics and research areas such as program and activity adjacency studies, safety keep out zones, topographical and geological surface requirements for infrastructural development, protected areas for science and research, and more. An ultimate goal of the study is the advancement of a collaborative parametric development model for Lunar infrastructural development that enables and accounts for rapidly changing needs and interests from science, commercial, and governmental organizations and institutions.
A parametric and data-driven framework enables preemptive solutions at the infrastructural scale that account for, recognize, and ameliorate the needs and interests of multiple surface construction and development stakeholders in ways that are informed, intelligent, and anticipatory of future growth and development at an urban scale. Anticipating that key infrastructural elements such as landing pads, roads, and utilities such as communication and power lines will be shared by multiple Lunar surface actors, we encourage the development of shared requirements for such infrastructure elements, in addition to the creation of knowledge communities and opportunities for open source knowledge transfer to actively engage and contribute to the development of said requirements and parameters at an urban scale.
As a leader in large-scale additive manufacturing solutions, ICON is developing technology solutions for on-demand manufacturing of various surface elements of Lunar infrastructure and civil engineering. Project Olympus is ICON's multi-year initiative to develop an autonomous, large-scale construction system capable of manufacturing horizontal and vertical structures on the Moon and eventually Mars. Project Olympus introduces design schematics for critical surface infrastructure necessary to realize a permanent Moon base, and envisions the construction of durable, self-maintaining, and resilient surface structures enabled by advanced 3D-printing technologies. ICON is developing Project Olympus in support of the Moon-to-Mars Planetary Autonomous Construction Technology (MMPACT) project; the goal of which is to develop, deliver, and demonstrate on-demand capabilities to protect astronauts and create infrastructure on the

lunar surface via construction of landing pads, habitats, shelters, roadways, berms and blast shields using lunar regolith-based materials].
Terrestrially, ICON is not only a service provider and design-builder for development-scale automated construction projects, but is also actively engaged in master planning and urban-scale development for the communities it builds. Large scale automated additive construction is a disruptive technology capable of delivering housing and other building typologies at production scales never before witnessed in traditional construction practices. Automated construction technologies enable the rapid re-development and creation of new communities and urban centers, while also enabling opportunities for ground-up solutions addressing warranted social, ecological, and economic solutions for the respective communities. Our study demonstrates how similar data-driven approaches to urban and master planning at the Lunar south pole enable new opportunities and added value for shared infrastructural development, and lays the foundation for future discussions on land use and regulatory frameworks at the south pole to more fully develop.

Keywords: masterplanning
3d-printing
additive manufacturing
ISRU
base planning
land use
infrastructure
lunar

01:40 PM **454 - Understanding the effects of moonquakes on the lunar infrastructure based on the data obtained from ALSEP**

Nerma Caluk - Florida International University, Dean Whitman - Florida International Univeristy

Abstract: NASA's plan to return humans to the lunar surface with the Artemis program and the fast growth of commercial space companies require an understanding of the structural response of future habitation components and systems on other planetary bodies that have drastically different environmental factors from Earth such as lower gravity, meteorite impacts, and low atmospheric pressures. One concern is lunar seismic events known as moonquakes. To fully understand the effects of seismic activity on the surface infrastructure, no matter the planetary body, a connection between the science of seismology and the structural engineering of the infrastructure needs to be well-defined and applied. Once the connection has been established, the missing data and knowledge gaps need to be assessed to provide for structurally stable, efficient, and sustainable lunar infrastructure designs that take into consideration both the structural integrity and fatigue of the building due to the prolonged seismic events, and the serviceability of the highly sensitive infrastructure and experiments onboard the surface habitat. Four different moonquake types are mentioned, with a focus on the most energetic ones, the shallow moonquakes. Different applications of the limited data for preliminary analysis were mentioned, while also stating the missing data points for future, more realistic and accurate design and analysis. An example of shallow moonquake event amplification has been described and applied in the structural assessment of a lunar base concept that was part of the first author's dissertation research.

Keywords: NASA
Artemis
Lunar Infrastructure
Seismic Design
Moonquake

Signal Processing
Civil Engineering
Structural Engineering
Seismology

02:00 PM **6531 - A PORTABLE SCALABLE HIGH ENERGY DENSITY TECHNOLOGY FOR POWERING SPACE MISSIONS INCLUDING SURFACE OPERATIONS DURING LUNAR NIGHTS**

Robert Moses - Tamer Space, Sang Choi - NASA Langley Research Center, Dennis Bushnell - Retired, NASA Langley Research Center

Abstract: A new direct energy conversion concept called Nuclear Thermionic Avalanche Cell (NTAC) combined with a Metallic Junction Thermoelectric (MJ-TE) generator, both invented and patented by NASA, offers high specific power that uniquely scales from milliwatts to megawatts enabling portable, at point of use utilization for every-thing space from propulsion to spacecraft, satellites, rovers, ISRU (In Situ Resource Utilization), habitats, and other mission systems[1-2]. Estimates based on experimental results and theoretical analyses suggest superior performance compared to radioisotope thermoelectric generators (RTG) by up to two orders of magnitude for the NTAC and three to four times better for the MJ-TE generator for the same mass. The NTAC technology uses energetic photons and beta particles from a variety of radioisotopes including nuclear waste to liberate a large number of intra-band (IB), inner shell electrons of atoms (105 C/cm3) through the bound-to-free transition by high order interactions of gamma-ray photons and beta particles (100 keV to MeV). The MJ-TE technology uses Seebeck junctions between two different metals to generate higher carrier mobilities between hot and cold surfaces (~10^3 C/cm3 from 10^23 atoms/cm^3). In contrast, conventional power generation uses low-grade energy yielding poor specific power because their intensity of energy can only allow the bound-to-free transition of the valence band electrons (3 C/cm^3) of the semiconductor or outer-most band electrons (8×10^3 C/cm^3) of the conductor atoms.

The key aspects of an NTAC are explained by the sequential photoionic interactions of high energy photons, including energetic beta particles, with atoms in material through primary, secondary, tertiary, and possibly higher-order couplings. These aspects were proven by laboratory experiments performed for photoionic emission of intraband electrons with a 320 keV γ-ray source. The experimental data showed that the emission current by the photoionic process was measured to be more than 40% greater than the primary interaction alone.

The key features of the NTAC system include the use of a high-grade energy source, such as γ-ray (> 100 keV) and x-ray (2 keV – 100 keV) photons and energetic β-particles (> 10 keV), that enables multiple successive interactions, resulting in greater power generation capability and the power scaling from mW to MW which is determined by the amount of radiation source.

Power output of an NTAC was estimated for a selected radioisotope. Theoretical estimates were based on experimental data. The efficiency of an NTAC is regarded to be very high (> 40%) because of the experimentally proven chain of multiple interactions and liberation of avalanche electrons by high-grade energy.

At a conceptual level, a mobile power station hosting 4 NTAC units rated for either 100 kWe or 200 kWe, based on the mission scales, could deliver electrical power to clients at mission locations. Total weight and total power of the 4 units of NTAC rated with 200 kWe power output are 1276 kg and 800 kWe, respectively, which are 5 times lighter than the weight of a fission reactor [3] and provides 20 times more power delivery.

This paper compares NTAC's performance with other power generation technologies and provides an update on prototyping tests to verify performance for powering many Earth and Space applications.

[1] Choi, S. H., Bushnell, D. M., and Moses, R. W., "A Portable High-Density Power Technology for Space, Lunar, and Planetary Applications," AIAA-2022-1911, January 3-7, 2022.

[2] Bushnell, D. M., Choi, S. H., and Moses, R. W., "Applications for a New Scalable, Low Weight, High Power Density Nuclear Battery and Thermal Electrics," NASA/TM-20220019348
[3] Rucker, M.A., "Integrated Surface Power Strate-gy for Mars", Nuclear and Emerging Technologies for Space 2015. Albuquerque, New Mexico, February 2015.

Keywords: Portable scalable high-energy density power technology
Survive the lunar nights
Lunar power
Rover power technology

02:20 PM **8087 - Trials & Tribulations of Asteroid Mining**

Alex Ellery - Carleton University

Abstract: Lunar industrialisation will require access to bulk asteroidal resources – our lunar industrial ecology requires nickel, cobalt, tungsten, selenium, carbon, water, etc. For example, Ni is corrosion-resistant and is a good substitute for copper for wiring, provides the basis for multifunctional alloys and is commonly used as a catalyst. Asteroids possess a unique range of useful materials, both bulk and exotic, that are absent or scarce on the Moon. Thus, asteroid mining widens the range of material functionality available on the Moon but asteroid mining imposes considerable technical challenges. Such materials require excavation from asteroidal material, physical comminution and beneficiation and chemical refining into feedstock for manufacturing into specific products. There are two approaches to accessing asteroidal resources: (i) source asteroidal deposits on the Moon that are expected to be available though as-yet undiscovered; (ii) source asteroids from the Near-Earth Object (NEO) population. We consider the latter. The main technological challenges are (i) the problem of Δv maneouvres, and (ii) the problem of milligravity operations. We shall examine these problems and potential resolutions. The specific materials offered by asteroids that are scarce on the Moon include NiFe metals of M-type asteroids, carbon from C-type asteroids and enstatite from S-type asteroids. This immediately introduces problem (i) so multiple asteroid mining operations will require coordination (such as a market-inspired algorithm incorporating jobshop planning with Δv maneouvering). Problem (ii) arises due to the milli-g environment of asteroids whereby asteroid mining operations will require anchorage by harpoons, penetrators, drills and/or moles. Such approaches cannot support surface mobility but can support fixed installations. A typical asteroid mining scenario involves mining asteroids in-situ and transporting desired extracts or manufactured products from the supply location to another demand location. A variation on this is acquire a fragment of the asteroid or entire small asteroid and transporting it under control to a manufacturing location. We envisage this site to be the Moon's surface where the technological problems of asteroid mining are diminished by partial gravity. We envisage the installation of an array of electromagnetic launchers/mass drivers on the asteroid that utilise local material as high-mass reaction mass for rocket thrust. These electromagnetic launchers would be supported by a Fresnel lens/thermionic conversion power generation system to charge flywheel batteries for powering the electromagnetic launchers – a renewable technology. We shall show that maneouvering asteroids to the Moon is feasible. The terminal lunar landing phase may be achieved through two methods: (a) impact; (b) soft landing; (c) intermediate hard-landing. The choice requires consideration of cratering against gravitational retention of asteroidal resources on impact and the degree of hard landing against landing site excavation by accelerated asteroid material. Although our goal is to supply bulk metals onto the Moon, a byproduct will be the supply of PGMs of high monetary value.

Keywords: Asteroid mining
In-situ resource utilisation
Asteroid propulsion

Electromagnetic launchers/mass drivers

02:40 PM **1894 - Decommissioned Fighters as Airborne Launch Platforms for Space Operations**

Piotr Zalewski - Military University of Technology, Łukasz Kiszkowiak - Military University of Technology, Stanisław Kachel - Military University of Technology, Robert Rogólski - Military University of Technology, Michał Frant - Military University of Tec

Abstract: The work is the result of the project funded by the Polish Ministry of National Defence. The study proposes an alternative (i.e. air-assisted) system for launching payloads (micro-satellites) to space using rockets fired from Su-22 or MiG-29 combat aircraft. The project verifies and evaluates such an air-assisted rocket system used for launching payloads to Low Earth Orbit (LEO) in many aspects.
Mission profile and rocket drop maneuver concepts have been developed. From the adopted model of calculations and simulation results, it follows that in the considered configuration, the aircraft can accomplish a mission in which a payload of at least 10 kg is launched into Low Earth Orbit.
The analyses were complemented by simulations and wind tunnel tests verifying the impact that space rockets may exert on the aerodynamic and mechanical properties of the carrier aircraft. Results of numerical simulations and wind tunnel tests to which models of the air-assisted rocket launching system were subjected indicate that the impact the rocket has on the aerodynamic characteristics of the aircraft and on its in-flight properties is negligible.
Similarly, load and strength tests to which the airframe's load-bearing structures have been subjected also failed to show any significant changes or deformations caused by the space rockets attached.
The system proposed may be deemed as the so-called Responsive Space Assets for the Armed Forces. Implementation of such a system not only offers independence from countries or commercial companies providing space services, but also allows to master new capabilities in the context of deploying satellite systems for safety and defense purposes.

Keywords: aircraft rocket space system
air launch
decommisioned aircraft

03:00 PM **19 - Korea's Space Vision: Opening of KASA and Building a Global Cooperation Network**

Tai Sik Lee - Professor Emeritus of Hanyang University and President of KOFST, Jinyoung Lee - Ph.D Candidate, Hanyang University, Yoonsun Lee - Research Professor, Hanyang University

Abstract: The presentation will discuss the opening of Korea's space vision and building a global cooperation network.

Keywords: space vision
Korea
global cooperation

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April 15 - 18, 2024; Greater Miami, FL

FIU | Engineering & Computing
Moss School of Construction, Infrastructure and Sustainability

Thursday April 18, 2024: Afternoon Session

Session Title: Robotic Construction and Outfitting Advancements to Support Functional Buildings and Infrastructure in Earth, Moon and Beyond

Session Co-chairs: Naveen Kumar Muthumanickam, Ph.D. (National Renewable Energy Lab NREL, Boulder, CO) and Nipesh Pradhananga, Ph.D., P.E., (Florida International University, Miami, FL)

Room 115

01:20 PM **366 - *Exploring Task Performance and Mental Workload in Time-Delayed Teleoperation for Extraterrestrial Construction***

Miran Seo - Texas A&M University, Youngjib Ham - Texas A&M University

Abstract: Humans have endeavored to build sustainable habitats on extraterrestrial planets to explore space. Building planetary surface habitats has become feasible with the advanced technology in teleoperation. We must conduct surveying, excavation, and site preparation for habitat construction; however, there are many challenges and uncertainties that need to be addressed, such as microgravity, regolith dust, and extreme environments. Under those inherent environmental constraints, a robust teleoperation system is key in successful mission task completions on the lunar surface. Unfortunately, in a Deep Space Network (DSN) communication system, a time delay inevitably occurs in data processing or signal transmission, and in turn it affects operators' performance and mental workload by degrading physical controls, telepresence, and situational awareness during work. We developed virtual Moon surface environments where teleoperators carry out construction tasks during the site preparation phase to evaluate the task performance and mental workload in time-delayed conditions. Through the experimental study, we explored how time delay degrades the operator's work performance and increases mental workload. Also, we examined the operator's behavioral changes caused by latency and analyzed varying physiological data in different latency conditions. The outcomes will shed light on how to explore latency by considering bandwidth and data storage limitations to identify the latency and human interaction effects in extraterrestrial construction.

Keywords: Human-Machine Interaction
Extraterrestrial Construction
Latency in Teleoperation
Robotics and Control

01:40 PM **2984 - Identification of Surface Defects of 3D Printed Concrete Structures Using Computer Vision and Machine Learning**

Zachary Graham - University of Tennessee Knoxville, Reese Sorgenfrei - University of Tennessee Knoxville, Hongyu Zhou - University of Tennessee Knoxville

Abstract: With the continued interest in the applications of 3D-printed concrete structures, it is of the utmost importance to be able to identify, quantify, and eventually ameliorate errors and defects that occur during printing and curing. The layer by layer deposition process allows for

greater flexibility compared to traditional form casting methods but can also act as an additional vector for errors in the final structure. Variations in layer adhesion, deposition rate, material consistency, settling during the printing, and in expansion/contraction during curing can all contribute to a final structure that deviates from the original design. As such, being able to address these as they occur during the manufacturing process is a critical component in expanding the use of additive manufacturing and automation in the construction of 3D printed structures.

The identification and quantification of geometric deviations and surface defects are centered on a combination of AI vision cameras to generate point clouds of the printed concrete structure as it is being deposited, post printing, and post curing. Human inspection of these point clouds and the physical print allows errors to be quantified and their effects on the final product tracked, with the eventual goal of automatic identification and remediation. This process leverages the models and information inherent in the use of additive manufacturing. The digital model that the printer is replicating serves as a prime to compare the point cloud against for describing variations from this intended result and the source of those variations across the manufacturing process. Point cloud generation is performed using an array of AI vision cameras, which feature both on-device depth calculation and with abilities for neural network computation. Open source software resources including DepthAI, OpenComputerVision, and Open3d are run both on the host computer and the cameras themselves to generate and save the point cloud. The benefits of a setup such as this compared to traditional LiDAR scanners are ease of scalability, lower cost, and included on-device and remote computation. Multi-camera configurations are tested on site with printing equipment and monitored remotely in real time for a fraction of the cost of a single LiDAR scanner. This research presents an example of how AI-empowered computer vision can be used for the printing error and surface defects identification of 3D printed concrete structures.

Keywords: Concrete 3D Printing
Error Identification
Computer Vision
AI

02:00 PM **9197 - Modeling Deformable Linear Objects for Autonomous Robotic Outfitting of Lunar Surface Systems**

Amy Quartaro - Virginia Tech, John Cooper - NASA Langley Research Center, Erik Komendera - Virginia Tech, Joshua Moser - NASA Langley Research Center

Abstract: This paper presents structural models of deformable linear objects (DLOs). DLOs are a subclass of deformable objects that encompasses common outfitting elements such as cables and ropes. Models are validated through hardware experiments, and integration in a robotic autonomy architecture for space environments is discussed.

A persistent human presence on the lunar surface is one of the next major milestones in space exploration. This requires the development of robust extraplanetary construction technologies including structures and materials modeling and robotic systems. Previous robotic construction technology development has primarily focused on structural assembly, with significantly less focus on robotically performed outfitting tasks to instantiate subsystems providing power, data, life support, etc. These tasks involve manipulation of highly flexible elements, which are difficult to model, such as cable harnesses, ropes, and hoses. Robotic manipulation of DLOs, especially cable harnesses, is an active area of research as cable harnesses are essential for providing power and data to space assets. DLO models that can be used for robot manipulator trajectory generation are necessary for autonomous operation of lunar infrastructure.

There are many proposed methods for modeling DLOs, and they primarily fall into three types: 1) discrete model-based, 2) continuum model-based, and 3) Neural Network-based. These types each have pros and cons, and the tradeoff between model accuracy and computational speed

informs which type should be used. An understanding of this trade-off is imperative for real-time control of autonomous systems. High computational requirements reduce the speed of the model, making real-time control difficult, while accuracy is critical to preventing collisions. Discrete models, such as a mass-spring multibody representation, require relatively few calculations, and accuracy is directly tied to the step size of the discretization. Continuum models, such as a B-spline representation or a Cosserat rod model (a mix of continuous and discrete), are more informed of the structural properties of the cable and are much more accurate than a rigid body mass-spring model, but at significant computational cost. A Neural Network approach can provide an online solution with very few computational steps, but properly generating training data can be difficult and validation for an in-space application is not trivial.
This paper explores the trade-off between different modeling approaches and compares accuracy and computational speed/complexity of the three types mentioned above. Model accuracy is evaluated using a cable in a static configuration. True cable shape is obtained using a depth camera for RGB images and point-cloud segmentation. The purpose of this experiment is to evaluate the trade-offs of different approaches to the DLO modeling problem.
Understanding the tradeoffs between different cable modeling techniques paves the way for developing robotic control and planning architectures necessary for real-time manipulation of DLOs for lunar infrastructure outfitting. Real-time control is required for robotic systems to be able to actively manipulate a cable in a harsh environment where model and sensor errors compound, and environmental conditions can cause significant disturbances. Cable routing must be performed in areas with high density of objects/obstacles: through truss structures, near solar panels or mirror arrays, next to bundles of electrical equipment. Understanding the best way to plan and manipulate a cable without disrupting the environment or damaging the cable is imperative to robotic outfitting operations on the lunar surface.

Keywords: Outfitting
Robotics
Lunar Surface
Deformable Linear Objects
Construction

02:20 PM **9444 - Robotics for systems integration in buildings – Pilot study of viable approaches**

Naveen Kumar Muthumanickam - National Renewable Energy Laboratory (NREL), Luke Boyd - Colorado School of Mines, Shanti Pless - National Renewable Energy Laboratory (NREL)

Abstract: The Industrialized Construction Innovation (ICI) team at the National Renewable Energy Laboratory (NREL) has been exploring the use of robotics to integrate thermal, mechanical, electrical, and plumbing systems in prefabricated building assemblies (offsite) and 3D printed buildings (onsite). Such multi-system integration tasks often require specialized robots and custom end-effectors for handling a range of rigid and non-rigid building system components. This paper presents pilot studies showcasing the use of robotics for a variety of systems integration tasks such as picking and placing structural studs, hygrothermal control layers, windowpanes, mechanical, electrical, and plumbing components (conduits/electrical raceways/outlets) in specific positions within prototype building assemblies. Specifically, comparisons of computational toolpath simulations of such robotic processes and real-life demonstration of the same shall be covered. Insights about how specific design for manufacturing and assembly (DfMA) principles helped in the optimal fabrication of the various systems and selection of appropriate robotic end effector hardware for various object manipulation tasks shall also be discussed. Additionally, details about a computational environment (under development) that is capable of programming and simulating the inverse kinematics of multiple form factors of robots (robotic arms, rovers etc.) with custom end effectors and payloads within a singular environment shall also be covered. Learnings and insights from such robotic construction pilots in terrestrial construction

can potentially lend itself for applications such as robotic outfitting of facilities in extra-terrestrial environments.

Keywords: Robotic Assembly
Building Systems
Systems Engineering
Toolpath Simulation
Design for manufacturing and assembly

02:40 PM **4464 - Development of an autonomous site preparation vehicle for the Moon**

Christopher Dreyer - Colorado School of Mines, Adrew Petruska - Colorado School of Mines, Neil Dantam - Colorado School of Mines, George Sowers - Colorado School of Mines, Kevin Cannon - Colorado School of Mines, Jamal Rostami - Colorado School of Mines,

Abstract: The ASPECT project (Autonomous Site Preparation: Excavation, Compaction, and Testing) is developing a vehicle and methods to clear, grade, and compact sites on the Moon for the construction of a lunar landing pad. A mobility platform is provided by Lunar Outpost with lightweight wheels developed by Mines. A straight dozer blade will be used to move regolith and rocks. A compaction system is being developed by Michigan Tech. Localization and controls are developed by Mines. Mines have developed autonomy and task planning. The ASPECT system will be tested in a 125 m3 testbed with simulated craters and rocks, containing a CSM-LHT variant. A 10 m diameter area will be demonstrated to be cleared, leveled, and compacted. Finished state requirements are level within 1 deg, smooth to 1 cm RMS, and compacted to 90% relative density to a depth of 30 cm. To simulate the low gravity of the Moon while tests are conducted in 1g, the ASPECT vehicle mass is 1/6 the mass that it would have on the Moon. On the Moon the vehicle will be 500 kg, but for testing in 1g mass is limited to 83 kg. Significant effort has gone into light weighting the system, particularly the vehicle chassis and wheels while removing batteries.
The development of lunar robotic systems requires test environments that mimic the performance a robotic system would have on the Moon. Terramechanics, the performance of mobility systems, is governed by the vehicle's interaction with the soil surface. As lunar surface gravity is 1/6 Earth's gravity, the difference in ground reaction force is significant. Several methods have been developed to simulate the terramechanics performance of a vehicle on the Moon while testing in 1g, including weight offloading rigs that actively lift 5/6 of the vehicle mass, scaling of rover wheels such that performance in 1 g is similar to performance in 1/6 g, and development of a reduced mass vehicle for testing in 1 g, the approach taken in ASPECT. Weight offloading rigs are the most common approach. They actively remove vehicle weight but operate over a limited area. A well-executed weight offloading rig will rapidly respond to changes in vehicle pose as it traverses a landscape. Wheel scaling relies on reference tests conducted on 1/6 g flights and constitutive equations that describe wheel terramechanics performance on lunar regolith. Wheel scaling has not been well explored and risks changing to rover dynamics. Reduced vehicle mass while maintaining the size of the anticipated lunar vehicle is conceptually simple but an engineering challenge. We have solved the challenge in ASPECT by removing all battery mass and using tethered power, by designing several systems to be low mass (wheels, vehicle chassis, and compactor). While feasible for APSECT, the reduced mass approach may not be feasible for all mobility systems. It should be noted that none of these approaches de-weight the regolith. A rover technology developer should be aware of the capabilities and limitations of conducting lunar-relevant tests in 1 g and select the most appropriate test method available for their system.
This paper will review the progress of the ASPECT project. The ASPECT vehicle will be operational and in the early stages of verification at the time of paper submittal. The ASPECT testbed at CSM will be in development. The paper will include a discussion and justification for the chosen approach to lunar-like gravity testing and the pros and cons of the approach relative to alternatives.

Keywords: terramechanics
lunar landing pads
lunar test beds