SKYLIGHT: A MISSION CONCEPT FOR IN-SITU INVESTIGATION OF THE MORPHOLOGY, GEOLOGY AND MINERALOGY OF LUNAR PITS. W.L. Whittaker[1], H.L. Jones[1], J.S. Ford[1], K. Sharif[2], U.Y.. Wong[2], [1]Carnegie Mellon University (Robotics Institute, 5000 Forbes Ave, Pittsburgh, PA, {red|heatherljones}@cmu.edu), [2]NASA Ames Research Center (Moffett Blvd, Mountain View, CA 94035).

Introduction: Lunar skylights are windows to unknowns both within and below the Moon's surface. Lunar pits are windows to unique science since the walls offer the only observable pristine geology on the moon [1,2,3]. They are unique opportunities to observe vulcanology, morphology, mineralogy and much more.

If accessible, lunar caves could be havens from the radiation, temperature and micrometeorite hazards of the Moon's surface [4]. Though immense caves are known to exist, none are yet known to be accessible. The discovery of hundreds of pits over the last decade raises the possibility that some of these could be long-dreamed-of havens.

Though discoveries to date have been from orbit, surface robots will make the next great explorations. The scenario is to rove a pit rim with a micro-rover, peer into the pit, acquire images of walls, floor and caverns, and to generate pit models. The mission is a low-cost, high-return, economical enterprise that is deployable on the small landers of our time. Its rover is a near derivative of the micro-rover destined for the lunar south pole aboard CLPS 19-C in 2022. Portions of the operations are necessarily autonomous since a small rover for this class of mission can't carry direct-to-Earth radio for human supervision or guidance when beyond the range of lander comm. Pit Exploration autonomy, In-situ pit modeling, and Lunar micro-rover mechatronics enable this class of mission.

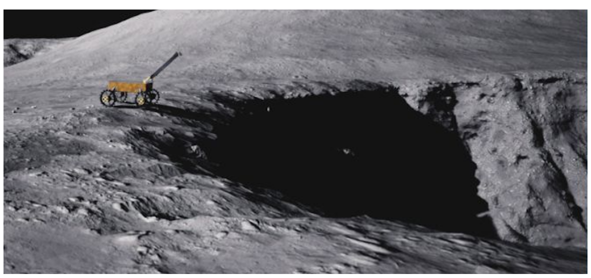

Fig. 1: Rover approaching a pit rim in simulation [Image: Neil Khera]

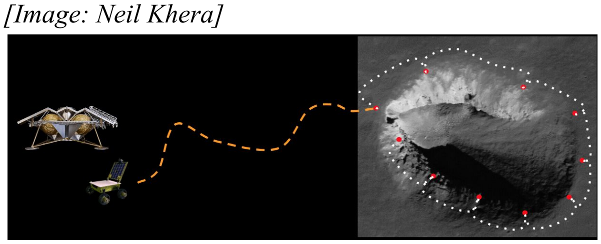

Fig. 2: The rover traverses from the landing location to the pit, then around the pit and to vantage points. [Pit image: NASA/ASU]

Pit Exploration Autonomy: Pit Exploration Autonomy generates the plans, behaviors, and imaging decisions for guiding the rover to acquiring the requisite imagery from vantages around the rim. The autonomy directs the rover to occupy strategic overlooks, acquire thousands of relevant images, and periodically transmit these to the lander. Overlooks are identified by balancing the value of imagery against the risks encountered at the rim. At each overlook telescopic images are acquired at many pan/tilt and exposure combinations to view the walls and floor.

High-cadence stereo perception and fast replanning then guide the rover in continuous motion with excellent localization and mapping. This exhibits a leap of quality, speed and traverse accuracy beyond prior rovers. The speed is essential to completing the mission in a single illumination period since this class of mission lacks the ability to endure lunar night.

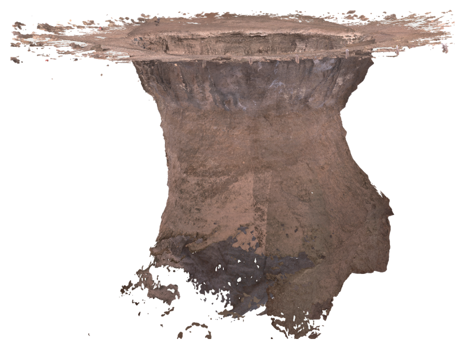

Fig. 3: High-fidelity model of the West Desert Sinkhole generated by photogrammetry [4]

Pit Modeling: The pit model is a primary data product of the mission since it is basis for the morphologic study, cavern discoveries and spatial correlation of all other data. The intensive processing to compute such models is straightforward on Earth, but unprecedented for small space-rated computing. Skylight achieves this by pre-processing onboard the robot to reduce image count and transfers the imagery to the lander for modeling. Although the resulting pit models are extremely accurate and detailed, their size is negligible relative to the raw imagery that couldn't possibly be downlinked to Earth.

The thousands of raw images are vastly reduced in number aboard the rover by computing single, well-lit images from the many obtained at high and low exposures. Redundant overlapping images are then pruned. A few larger images are then mosaiced from the smaller images. These steps vastly reduce the dimensionality of the geometric pit model computation. Incremental photogrammetry processes subsets of these images over the course of the mission versus batch processing all the images at mission end. This ensures that early pit models reach Earth, improves models as more images arrive, and ultimately results in a highest-possible quality pit model.

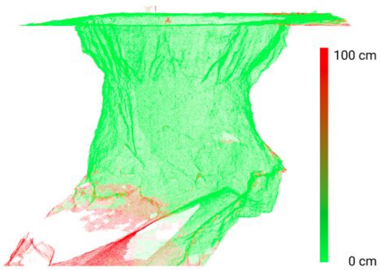

Fig 4. High-coverage, high-fidelity pit model colorized to show error between vision-generated and LIDAR surveyed actual. Errors are less than 10cm across 95% of the pit surface [5].

Lunar Rover Mechatronics: Rovers for these small pit exploration missions must necessarily be distinct from those that have come before. They must be compatible with small landers, negotiate steep pit aprons, provide powerful computing, and obtain the required cross-pit images. Great advantage comes from deploying the pit camera at a high forward reach into a pit. PitRanger is a terrestrial prototype of design leveraged from the MoonRanger polar mission rover that fulfills these requirements.

To survive launch vibration with minimal mass, PitRanger is a rigidly-suspended 4WD skid steer. This prioritizes delivery to the surface over surface performance. Aggressive slope ascent is achieved by uphill biasing of weight to equalize wheel downforce and rimpull. Rovers are easily entrapped by attempting turns on steep, soft terrain, so the rover reverses versus pivoting for ascent. Stereo navigation cameras are both fore and aft to safeguard reversal.

The terrestrial engineering model incorporates these features for practical experimentation while the program evolves the design for space relevance.

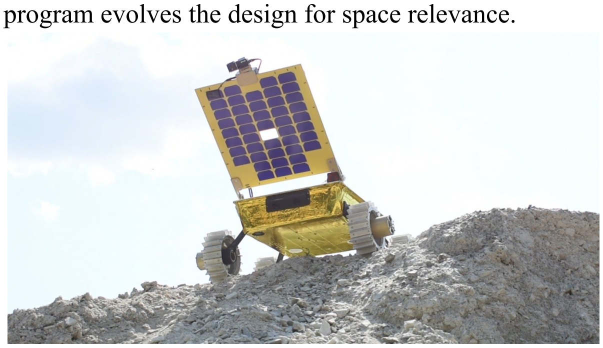

Fig. 5: Micro-rover engineering model

Instruments: A High-Res Monochrome Camera enables detailed photogrammetry of the pit. A NIR Spectrometer facilitates investigation of pit mineralogy.

Mission Specifics: This mission benefits immensely from a precision lander with good control authority because (1) An ideal EDL trajectory would provide low, slow flyover of the pit [6]. This would facilitate flyover pit modeling akin to a drone from perspective never attainable by the surface rover, and (2) The closer the landing is to the pit, the less traverse distance to reach the pit and the less shuttling by the rover to remain in or return to lander comm range for relay to Earth. Mission length is constrained to a single day, but the rover is capable in that time of exploring the largest of collapse pits or several small pits in a pit chain or impact melt. The PitRanger micro-rover and incorporated instruments have a mass of 20 kg. Flight development cost is on order of $10M due in large part to technical advantages and economies from analogy to the 2022 MoonRanger polar micro-rover.

Conclusion and Future: Small, affordable, high-value, near-term scientific lunar pit missions are viable. Specific high-performance robot mechatronics, autonomy and algorithms for pit modeling to support such missions are in advanced development. In-situ computation of high-fidelity terrestrial pit modeling has been exhibited on the computing baselined for this class of rover. A completely integrated, fully autonomous robotic exploration and modeling of the West Desert Sinkhole is planned for 2001 to exhibit the end-to-end capabilities in action. A proposal is currently under development for a PRISM-class mission, seeking a flight opportunity.

Acknowledgments: The developments presented here are supported by NASA's Institute for Advanced Concepts under grant #80HQTR19C0034.

References: [1] Haruyama J. et al. (2009) *GRL,* doi:10.1029/2009GL040635. [2] Robinson, M.S. et al. (2012) PSS 69, 18-27. [3] Wagner, R.V., Robinson, M.S. (2014) Icarus 237, 52-60. [4] Horz, F. (1985), "Lunar Bases and Space Activities of the 21st Century", LPI, p. 405. [5] Ford, J.S. et al. (2021) "Lunar Pit Exploration and Mapping via Autonomous Micro-Rover," *IEEE Aeroconf*. [6] Jones, H.L. et al. (2013) *LPS XLIV* Abstract #3080.