NOTE: This document was prepared by a team that participated in the 2018 Workshop on Autonomy for Future NASA Science Missions. It is for informational purposes to inform discussions regarding the use of autonomy in notional science missions and does not specify Agency plans or directives.

2018 Workshop on Autonomy for Future NASA Science Missions: Moon Design Reference Mission Reports

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Introduction

Autonomy is changing our world; commercial enterprises and academic institutions are developing and deploying drones, robots, self-driving vehicles and other autonomous capabilities to great effect here on Earth. Autonomous technologies will also play a critical and enabling role in future NASA science missions, and the Agency requires a specific strategy to leverage these advances and infuse them into its missions. To address this need, NASA sponsored the 2018 Workshop on Autonomy for NASA Science Missions, held at Carnegie Mellon University, October 10-11, 2018.

The Workshop goals included:

- Identifying emerging autonomy technologies (10-15 years) that will:
  - Enable or enhance mission capabilities
  - Reduce risk
  - Reduce cost
- Identifying potential collaborations, partnerships, or linkages involving government, industry, and/or academia to enable these technologies

Capturing crosscutting autonomy technology requirements for future NASA missions
Over 90 individuals from industry, academia, and NASA participated in the workshop, which included presentations by keynote speakers, panel discussions, and small group discussions.

To provide structure for workshop discussions and post-workshop analysis, NASA established eight teams to examine the following Design Reference Mission (DRM) areas: Astrophysics, Earth Science, Heliophysics, Mars, Moon, Ocean Worlds, Small Bodies and Venus. Each DRM team was led by a scientist and a technologist, and team members consisted of workshop participants with relevant experience and interest. NASA asked each team to develop one or more mission scenarios that would be enabled by infusion of autonomous technology. The Agency provided guidance to support these team discussions; in particular, NASA urged the DRM teams to "think out of the box" and to consider bold missions that would be enabled by autonomous technology to provide valuable science results. Each DRM team developed mission scenarios that included defined science objectives, capability and technology needs, system requirements, and a concept of operations. Teams also identified gaps where autonomy technologies and other supporting technologies need to be developed and/or infused to enable each mission.

The DRM teams conducted small group discussions at the workshop and then presented a summary of their findings to all workshop attendees. Each DRM team continued to refine its mission scenarios after the workshop, creating both a full report and a summary report to document team findings. DRM teams also reported results at the December 2019 meeting of the American Geophysical Union.

This document contains the full report and summary report generated by the Moon DRM team. Full and summary reports generated by all eight DRM teams, plus a summary of workshop results are available online.

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The Moon Design Reference Mission Report

Part I: Abstract

The Moon—the cornerstone of the solar system—is an ideal exploration target for humans and robotic explorers. The Moon provides a cornerstone upon which our understanding of many planetary processes is based. From the results of prior and ongoing missions, we have proved that the Moon is an attainable, interesting, and useful location—while confirming our understanding that there is still more to learn and explore. In particular, the Lunar Reconnaissance Orbiter (still operating in lunar orbit) has produced considerable advances in our understanding of how planets evolve, the impact cratering process, the evolution of volcanism, and how the space environment alters the surface. Future missions to the lunar surface will provide much-needed ground truth to tie together and relate some of the remotely sensed data products collected over the past several decades.

Autonomy can greatly enhance future exploration missions to the lunar surface as well as enable operations in extreme environments. Without autonomy, humans and robotic spacecraft have successfully navigated satellites, performed soft landings, deployed instruments, and returned samples to the Earth. With autonomy, future missions will have the ability to make mission-critical decisions such as those required to navigate and avoid hazards without the need for human interaction. This capability will enable the exploration of more extreme environments, reduce the delay in decision-making, and decrease the overall cost of mission operations. As the most accessible target in our solar system, the Moon is an ideal location to demonstrate new technologies. Due to this proximity, scientists and engineers can push the boundaries of autonomy while having the ability, in some cases, to service and update systems with astronauts on the surface or in orbit.

Future lunar exploration will leverage a variety of spaceflight capabilities, including advanced orbiters, landers, rovers, small spacecraft, and humans. The following Moon Design Reference Mission (DRM) scenarios illustrate ways in which autonomy can be incorporated to enhance and facilitate exploration to unexplored regions of our nearest neighbor.

Design Reference Mission Scenarios

The goals of the Moon DRM scenarios in this document are to explore new areas of the Moon and collect key new measurements to tie to remote datasets and answer important science questions. These DRM scenarios are not intended to be a comprehensive list of lunar missions, nor should these notional design reference missions be construed as being the only lunar missions that would benefit from leveraging autonomy technologies. Rather, these missions are generic scenarios where autonomy enables science and exploration while also advancing the use of autonomy deeper into the Solar System.

- A **long-duration, high-speed rover** is a surface-exploration mission designed to investigate hundreds of scientific sites over a 1000-km traverse during two Earth years. The goal of the long-duration, high-speed rover mission is to use autonomy to navigate and avoid hazards while it travels across the surface between a set of key waypoints. The rover and payload suite will acquire scientific measurements over a broad area and address many key scientific objectives.
- **Orbital polar resource explorers** would use small distributed systems to survey potential lunar surface volatile deposits from orbit to provide preliminary scouting of resource sites.
- A **sub-lunarean void explorer** would explore a void autonomously without user guidance and assess the utility of the sub-lunarean environments for human habitation and shelter while increasing the understanding of the history of mare volcanism and implications for other terrestrial planets.

Critical Autonomous Technologies

The critical autonomous technologies that will enable all three of these scenarios are **situation and self-awareness, reasoning and acting,** and **collaboration and interaction**, including:

- Sensing and perception
- State estimation and monitoring
- Knowledge and model building
- Hazard assessment
- Mission planning and scheduling
- Activity and resource planning and scheduling
- Motion planning
- Execution and control
- Goal and task negotiation

Supporting Technologies

The key supporting technologies required to achieve these DRM scenarios include:

- Light detection and ranging (LiDAR) –improve autonomous hazard avoidance
- Stereo imaging and processing –facilitate onboard processing and navigation tasks
- Inertial Measurement Units (IMUs) – advance state estimation and monitoring of operations

- Advanced onboard processing and modeling – enable situational awareness in decision making
- Cross-link communications – advance multi-robot and team exploration to increase return
- Machine-learning platforms/architectures – identify interesting targets of opportunities in bandwidth-limited situations

A summary of findings related to the Moon DRM scenarios is presented in Part IV.

Part II: The Case for the Moon

As described in the 2007 National Research Council's "Scientific Context for the Exploration of the Moon" report (Space Studies Board, 2007) and the 2011 Planetary Decadal Survey "Visions and Voyages" report (National Research Council Committee on the Planetary Science Decadal Survey, 2011), and subsequently restated in the 2018 Lunar Exploration Analysis Group (LEAG) "Advancing Science of the Moon" report (Lunar Exploration Analysis Group, 2018), advances arising from recent lunar missions produced dramatic new questions about lunar volcanism, volatiles, impact processes, lunar tectonics, and the lunar environment.

Furthermore, the Moon is the most accessible target for resuming human exploration beyond low-Earth Orbit, with vast and accessible resources, making it the critical enabling asset for any United States activities beyond low-Earth orbit (Committee on Human Spaceflight, National Research Council, 2014; Lunar Exploration Analysis Group, 2011; P. D. Spudis, 2016; P. Spudis & Lavoie, 2011). The Moon's importance is appropriately reflected in Presidential Space Policy Directive 1, which directs NASA to return United States Astronauts to the lunar surface for long-term exploration and utilization and directs NASA to land United States Astronauts on the lunar surface by 2024 as a prelude to the establishment of a permanent lunar surface facility by 2028.

As explicitly noted by the Advancing Science of the Moon Specific Action Team (ASM-SAT) report, surface exploration of the Moon is required to not only provide ground-truth for key orbital results, but also to make progress in addressing all key science and exploration questions. Goals and objectives for NASA lunar exploration are defined by the NASA Lunar Exploration Analysis Group in the United States Lunar Exploration Roadmap (US-LER), created by LEAG at the request of the NASA Advisory Council and developed through a comprehensive community engagement process that synthesized inputs from scientists, engineers, and policymakers.

Developing automation technologies to use on the Moon is a logical way of enhancing the exploration efforts on the Moon for both human and robotic exploration, with clear benefits for enhancing scientific exploration of the Moon as well as using developing lunar resources commercially. This concept is reflected in the fact that the "Feed Forward" theme of the US-LER explicitly calls for developing autonomy for lunar applications to most effectively prepare for voyages to destinations beyond the Earth-Moon system. Autonomy for lunar exploration is considered desirable in the US-LER for enabling long-duration traverses across the lunar surface while minimizing human or flight controller interaction with the surface mobility systems.

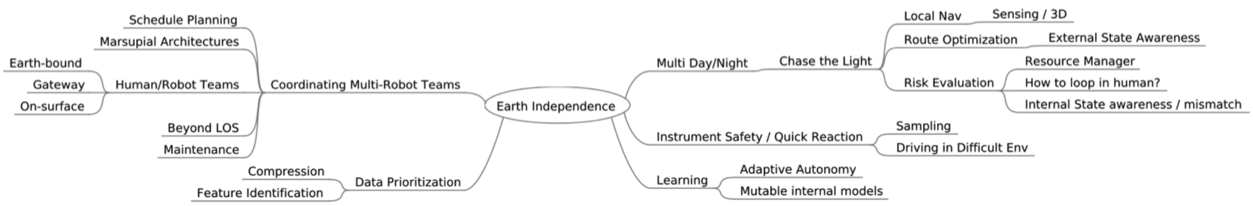

Fig. 1: Motivations for lunar exploration autonomy from workshop breakout discussions

Part III: Design Reference Mission Scenarios

Moon DRM Scenario 1: A Long-duration, High-speed Rover

The goal of the long-duration, high-speed rover mission is to use autonomous mobility to acquire scientific measurements over a broad area and address many key scientific objectives, including:

- Providing ground truth for all terrain types measured by orbiting spacecraft.
- Characterizing the composition of the components of the lunar regolith in order to provide important constraints on the lithologic diversity of the crust.
- Characterizing the lunar surface to investigate volcanic processes and increase our understanding of the evolution of the lunar crust.
- Investigating and quantifying possible magnetic anomalies and lunar-surface swirls.
- Creating a sample cache that could be retrieved by future human and robotic exploration systems.
- Detecting, assaying, and mapping potential resources to identify and quantify vital resource reserves to enable commercial exploitation.
- Quantifying the actual impacts of dust, its environments, and interactions with systems to validate lunar operational best-practices and impact future logistics and supply chains for human inhabitants.
- Measuring the radiation environment (primary and secondary) present on the lunar surface to inform future habitat design.
- Demonstrating applicability of advanced autonomy technologies to exploration of other destinations, such as Europa.

The Concept of Operations:

A long-duration, high-speed rover enables measurement collection and provides ground truth for remotely sensed data products over a wide range of geologic terrains (i.e., mare and highlands). To enable the long traverses, the onboard instrument suite will acquire most of the measurements while in motion or during short pauses. This concept is in stark comparison to the rovers studying Mars, which stop frequently for long periods to gather measurements. While this architecture limits the time for intensive studies of a particular site, the coverage gained by a highly mobile platform will increase the scientific return over a diverse set of geologic materials.

Over a range of over 1000 km, a series of high-priority targets will answer both scientific and exploration questions in a single mission. While there are many traverse options, one traverse example initiates in southern Oceanus Procellarum near the Reiner Gamma Constellation Region of Interest, continues through the Marius Hills volcanic complex, proceeds northward along the youngest mare basalts as defined by crater statistics (Hiesinger et al., 2011), and concludes with an in-depth exploration of the Aristarchus plateau **[Fig. 2]**. This traverse includes diverse lithologies, regions of unexplained albedo and color, magnetic anomalies, a wide range of lunar volcanic types and ages, and includes four Constellation Regions of Interest (Reiner Gamma, Marius Hills, Aristarchus 1 and 2) (Gruener and Joosten, 2009; Jolliff et al., 2010).

After landing on the lunar surface and performing the necessary checkout procedures for the navigation, communication and instrument systems, the rover will begin traversing toward Reiner Gamma and collecting science measurements. Lunar Prospector observations showed that the tadpole-shaped albedo signature (Reiner Gamma) is located on one of the strongest crustal magnetic anomalies (Mitchell et al., 2008). Using an onboard magnetometer, the rover can sample the magnetic field strength in detail to examine the distribution/structure of the crustal magnetic source and its correlation with albedo variations.

After exploring Reiner Gamma, the rover will autonomously navigate toward the Marius Hills region using the Cruise Mode. As the rover approaches the main site, the rover will begin visiting as many different volcanic features as possible to acquire high-resolution images of the diversity of volcanic features present (cones, domes, rilles, craters). Additionally, the rover will image the

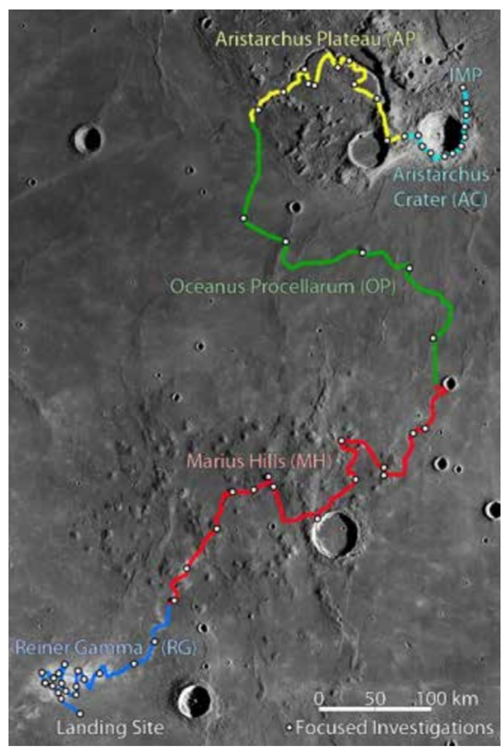

Fig. 2: Example of a long-duration traverse

surrounding regolith to better understand the variations in morphology and flows. Meanwhile, other instruments will map out the mineralogy of basalts across the region as well as examine the elemental abundances in the lava flows.

The rover will then travel to the Aristarchus Plateau. On the way, the rover will traverse over what is thought to be the youngest mare as determined by crater count statistics (Hiesinger et al., 2011). As it reaches the Plateau, the rover will begin to investigate the history of explosive volcanism at the site and begin to address questions about the depth of origin and composition of primary magma, degree of fractional crystallization, constraints on mare petrogenesis, and the composition of lunar interior. The rover will also sample the pyroclastic layer, examine its thickness using exposures created from impact events and evaluate its potential consumption for future in situ resource utilization (ISRU).

The traverse on Aristarchus Plateau closely follows the primary rille (Cobra Head), gaining in elevation and making its way to the Aristarchus Crater. Once at Aristarchus Crater, the rover will investigate the surface regolith to better understand the composition, structure, and variability of the crust. The rover will also survey the impact melts along with silicon-rich materials (southwestern rim) and olivine/glassy materials (southeastern rim). The overall goal is for the rover to identify and characterize at least four lithologies in Aristarchus Crater ejecta. Additionally, observations acquired along this traverse will help us better understand the impact history and the modification, redistribution, and mixing associated with impacts of this magnitude.
While this concept includes only a single rover, future missions and campaigns may implement multiple rovers and incorporate human explorers on the surface. These advancements will require communication and coordination between the robotic assets as well as the human explorer.

The Autonomous Capabilities Needed:

1. Autonomous Local Navigation

Autonomous local navigation is enabling for the long-duration, high-speed rover concept. To enable this mobility, the rover will have to collect measurements while in motion with either a LiDAR system or a set of optical stereo cameras. This information will be processed onboard to build a model of the surrounding environment. From the model, potential hazards will be identified, and an optimal traverse path will be computed without interaction with human controllers or computational resources on Earth. Finally, an IMU with the aid of an onboard computer will be needed to assess the current state of the explorer and to monitor the progress to ensure the system stays within the operating limits.
Using NASA’s Autonomous Systems Capability Leadership Team (AS-CLT) Taxonomy document as a reference, the autonomous technologies needed for this capability are:

- Sensing and perception
- State estimation and monitoring

- Knowledge and model building
- Hazard assessment
- Mission planning and scheduling
- Activity and resource planning and scheduling
- Motion planning
- Execution and control

2. Adaptive Autonomy

Adaptive autonomy builds on the autonomous navigation outlined above, but enables a human monitor to adjust a traverse or the measurement objectives based on new observations. This technology will enhance the capability and science return and provide a flexible architecture for science exploration.

Using NASA's Autonomous Systems Capability Leadership Team (AS-CLT) Taxonomy document as a reference, the autonomous technologies needed for this capability are:

- Sensing and perception
- State estimation and monitoring
- Knowledge and model building
- Event and trend identification
- Anomaly detection
- Execution and control
- Fault diagnosis and prognosis
- Fault response
- Learning and adapting
- Modeling and simulation

Other technologies that are needed to support autonomous and adaptive navigation are high-capacity computing power for onboard processing as well as machine learning platforms/architectures to identify anomalies and characterize the surrounding environment.

3. Multiple Robots/Assets Working in Coordination

As the size of an exploration region increases, multiple robots and assets working in coordination will enable new types of datasets and science. For example, multiple assets strategically spaced can be used together to monitor processes such as the mobility of volatiles in and around permanently shaded regions near the lunar poles. Likewise, an array of long-lived rovers can coordinate traverses and measurement tasks. If a large number of surface assets have a mobility component, it will not be possible to individually control and monitor using the standard operation methods used for Mars rovers. Therefore, the network of assets will need to communicate and coordinate with each other autonomously to identify the objectives of each.

Using NASA's Autonomous Systems Capability Leadership Team (AS-CLT) Taxonomy document as a reference, the autonomous technologies needed for this capability are:

- Mission planning and scheduling
- Activity and resource planning and scheduling
- Fault diagnosis and prognosis
- Joint knowledge and understanding
- Behavior and intent prediction
- Goal and task negotiation
- Operational trust building
- Verification and validation

Other technologies that are needed to support this autonomy are cross-link communications, team-level localization, and cooperative power sharing/distribution (wired or beamed power transfer).

4. Planning and Coordination in Multi-Robot and Human-Robot Teams

Future human missions may use mobile robotic assets to help collect measurements and complete maintenance tasks around a lunar outpost. As lunar ISRU technologies are developed and implemented, planning and coordination of multi-robot and human-robot teams will be required. The development of this technology will "feed forward" to NASA goals for sustainable human and robotic exploration of the Solar System.

Using NASA's Autonomous Systems Capability Leadership Team (AS-CLT) Taxonomy document as a reference, the autonomous technologies needed for this capability are:

- Sensing and perception
- State estimation and monitoring
- Knowledge and model building
- Mission planning/scheduling
- Activity and resource planning/scheduling
- Fault diagnosis and prognosis
- Fault response
- Learning and adapting
- Joint knowledge and understanding
- Behavior and intent prediction
- Goal and task negotiation
- Operational trust building
- Test and evaluation

Other technologies that are needed to support this autonomy are scheduling/planning in high-dimensional state spaces, with uncertain observations of environment and human performance, team actions, and shared beliefs.

Moon DRM Scenario 2: Orbital Polar Resource Explorers

As noted by the recent LEAG Advancing Science of the Moon Specific Action Team (ASM-SAT) report (LEAG 2018), the past decade has provided a wealth of new data and an abundance of research focused on understanding polar volatiles and the polar environment **[Fig. 3]**. Interest in the special environment of the lunar poles has grown dramatically, but an understanding of polar volatiles and the fundamental questions about their origin and evolution remain unanswered and will remain so without more mission results, including orbital measurements, in situ analyses, and returned samples. Many of the technologies outlined above for a long-duration surface exploration rover would also be highly applicable to the unique lunar polar environment, where intelligently and autonomously moving in and out of the sunlight is necessary to enable long-duration operations on the surface (Speyerer et al., 2016; Speyerer & Robinson, 2013).

The 2018 Space Resources Roundtable/LEAG Workshop on Lunar Polar Prospecting, along with the 2017 LEAG/ International Space Exploration Coordination Group (ISECG) polar volatile coordination dialog Specific Action Team, also highlighted the value of low-orbiting small spacecraft platforms **[Fig. 4]** at addressing measurement requirements between low-lunar orbital (LLO) and surface measurements (e.g., the notional Artemis-1 co-manifested LunaHMap mission). The Lunar Polar Prospecting Workshop (Morris and Sowers, 2018) suggested that a CubeSat swarm could be employed to gather high-resolution remote sensing data at the lunar poles relevant to the existence and characterization of volatile resources. In this scenario, CubeSats would fly as low as possible (10-20 km above the surface).

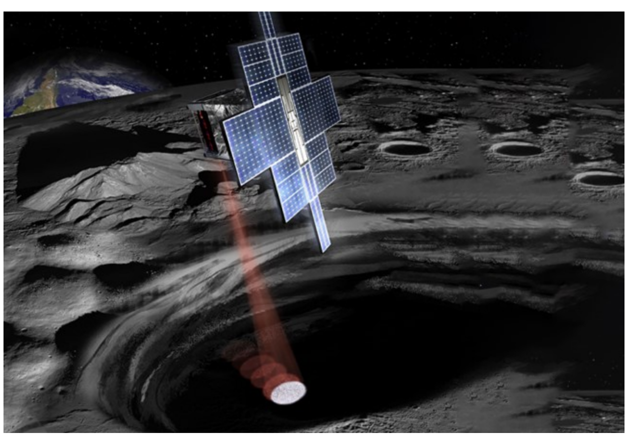

Fig. 4: The Lunar Flashlight mission, illustrated here, highlights the potential value of small spacecraft for lunar resource exploration.

Fig. 3: The Rim of Shackleton crater, a high-priority destination for future human and robotic exploration.

The Concept of Operations:

For this polar volatile explorer, multiple SmallSats would be engaged to fly over the polar regions at low altitudes (10-20 km above the surface). Through a series of coordinated measurements, the satellite array can aggregate their individual measurements which could then be synthesized into a high-resolution dataset covering numerous locations in the polar region to identify potential ice deposits. This same mission could also include the deployment of multiple (even hundreds) low cost impactors to provide needed ground-truth measurements. The impactors could be outfitted with instruments to detect and quantify the volatiles present in the permanently shaded cold trap.

The Autonomous Capabilities Needed:

Autonomous navigation and multi-robot communication /coordination are key capabilities needed to carry out this type of mission.

5. Autonomous Local Navigation

With potentially hundreds of SmallSats needing to coordinate, it is important that each be able to navigate and orientate autonomously and independently of ground-based controllers. This capability will reduce the need for manual commanding and communication during these measurement sequences. Each satellite will need the ability to localize itself relative to the target and other satellites in the network with low-powered IMUs and efficient star trackers. Using NASA's Autonomous Systems Capability Leadership Team (AS-CLT) Taxonomy document as a reference, the autonomous technologies needed for this capability are:

- Sensing and perception
- State estimation and monitoring
- Knowledge and model building
- Hazard assessment
- Mission planning and scheduling
- Activity and resource planning and scheduling
- Motion planning
- Execution and control

6. Multiple Robots/Assets Working in Coordination

The science measurements provided by this network of SmallSats are only valid when observations are carried out in coordination with each other. Therefore, the network of assets will need to communicate and coordinate with each other autonomously to identify the objectives and measurement sequences of each.

Using NASA's Autonomous Systems Capability Leadership Team (AS-CLT) Taxonomy document as a reference, the autonomous technologies needed for this capability are:

- Mission planning and scheduling
- Activity and resource planning and scheduling

- Fault diagnosis and prognosis
- Joint knowledge and understanding
- Behavior and intent prediction
- Goal and task negotiation
- Operational trust building
- Verification and validation

Other technologies that are needed to support this autonomy are cross-link communications and team-level localization.

Moon DRM Scenario 3: Sub-lunarean Void Explorer

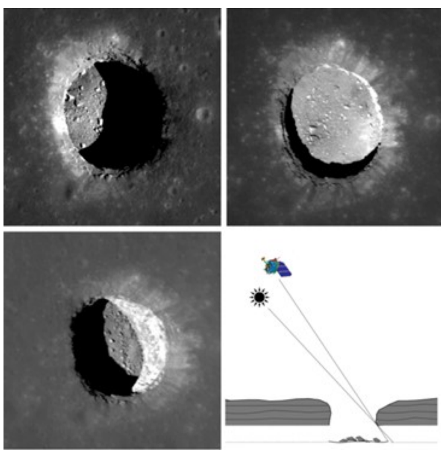

Fig. 5. Sublunarean void under different illumination conditions. **Fig. 6:** Sublunarean void explorer concept.

As outlined by the recent LEAG/Solar System Exploration Research Virtual Institute (SSERVI) Lunar Science for Landed Missions workshop (Jawin et al., 2019), data from the Japan Aerospace Exploration Agency (JAXA) Space Science SELenological and ENgineering Explorer (SELENE) and NASA Lunar Reconnaissance Orbiter (LRO) missions have resulted in discoveries of "skylights" or "pits" in mare basalts **[Fig. 5]** that have been interpreted as breached lava tubes (Haruyama et al., 2009a; Robinson et al., 2012; Wagner and Robinson, 2014), and the walls of these pits provide new information about mare basalt emplacement as a series of thin flows. Such pits provide a site in which a stratigraphic sampling of mare basalt lava flows could occur (along with paleoregolith). Such pits are also interesting destinations for human exploration, since they provide natural radiation shielding and a benign thermal environment. Entering and exploring a pit crater is a unique lunar science objective – the characteristics of these presumed lava tubes, including how far they extend into the subsurface, are presently unknown and further exploration is required. Since uncrewed precursor missions will have to operate outside of Earth line-of-sight while in a sublunarean void, autonomy is uniquely enabling for exploration and required to achieve Decadal objectives. Since the observed floors of the sublunarean voids are rough, other mobility technologies will be required to explore the voids. Both propulsive robotic spacecraft (Robinson et al. 2014) **[Fig. 6]** and advanced mobility systems (e.g., Whitaker, 2014) have been proposed.

The Concept of Operations:

In this design reference mission, a lander will use optical navigation to identify and lock on to the edges of the pit [**Fig. 5**]. As it approaches the pit, it will navigate down the center of the pit and enter at a slow vertical velocity (1 m/s) enabling imaging of the pit walls to better understand the layering present. As it approaches the floor, optical hazard avoidance will be used to avoid large boulders that have eroded off the pit wall and identify a safe landing location. Once landed and the immediate area around the landing site is characterized, a small spherical flying robot (Thangavelautham et al., 2012; Strawser et al., 2014) will be deployed. Lithium hydride and water/hydrogen peroxide will power a series of micro-thrusters that pulse and allow the spherical flying robot to explore the pit region. One of the main science questions is whether these features are just collapsed features or the opening to a large void space or lava tube. Without the ability for direct human control and navigation, the robot will have to determine its location, identify interesting targets, and explore the void space autonomously. This mission may include multiple deployable robots; in such cases, individual measurement tasks and communications will need to be coordinated.

The Autonomous Capabilities Needed:

As with the prior Moon DRM scenarios, local navigation and multiple coordination are needed to enable the mission.

7. Autonomous Local Navigation

These regions have never been explored and satellite observations provide little insight into what can be expected. For this mission to be successful, the lander and individual robots will need to navigate, avoid potential hazards, and relay back their positions without any human interaction.

Using NASA's Autonomous Systems Capability Leadership Team (AS-CLT) Taxonomy document as a reference, the autonomous technologies needed for this capability are:

- Sensing and perception
- State estimation and monitoring
- Knowledge and model building
- Hazard assessment
- Mission planning and scheduling
- Activity and resource planning and scheduling
- Motion planning
- Execution and control

8. Multiple Robots/Assets Working in Coordination

This mission architype will enable multiple propulsive robots to explore the lunar pit and potential lava tube. To maximize the science return, the multiple robots should work in

coordination to maximize the explored area and relay back the most comprehensive measurements of the pit's features.
Using NASA's Autonomous Systems Capability Leadership Team (AS-CLT) Taxonomy document as a reference, the autonomous technologies needed for this capability are:

- Mission planning and scheduling
- Activity and resource planning and scheduling
- Fault diagnosis and prognosis
- Joint knowledge and understanding
- Behavior and intent prediction
- Goal and task negotiation
- Verification and validation

The Relevant Research and Development Projects for these DRM scenarios

- Institutions researching Simultaneous Localization and Mapping (SLAM) and other self-driving technologies (multiple institutions)
- Sensor safety- i.e., avoiding pointing sensor at the Sun (NASA Ames)
- Planning for sensor limitations (Sun in field of view (FOV)/High Backscatter)
- Monitoring and characterization of rover health (e.g., solar availability)
- Sensor technology for detecting hazards
- Multi-robot teams (e.g, robot soccer, Department of Defense swarm projects such as the Defense Advanced Research Projects Agency's OFFensive Swarm-Enabled Tactics [OFFSET])
- Contemporary research in belief space planning and human-robot teaming
- Reduce risk by better characterizing/utilizing system capabilities
- Reduce risk by protecting assets more effectively
- Reduce risk of wasting science resources/mission life

The Potential Challenges, Risks, or Questions for these DRM scenarios

The working group identified several challenges that pose risk for all these scenarios and that could be addressed through application of autonomy:

- **Reduce risk by selecting safe traverses: avoiding slope and hazardous surface features when possible**
- **Reduce risk of mission failure due to limited operation time**
- **Reduce risk of mission lifetime reduction using optimized resource allocation strategies**

For all of these risks, we need to leverage contemporary work in natural language/understanding, psychology of human-robot teams, and human state/performance estimation.

However, maximum application of autonomy depends on the mission objectives. Risk reduction could also be achieved leveraging autonomy by enabling missions to visit more locations than a single short-duration rover, or to better reach an objective (i.e., get into a lava tube without communications with Earth), or to accomplish multiple objectives simultaneously. However, this could increase risk because of potential n^2 interactions (and thus increased complexity over single system missions).

Inherently, for this report we assume that multiple robots are too costly to operate from Earth, or that it is more efficient or effective for the robots to work autonomously (rather than with humans in the loop), or these robots have to operate when humans cannot be “in the ops loop” (e.g., no communication link from the Moon to Earth, Gateway, etc.). However, advances in technologies and/or launch vehicles may remove perceived risks and complexities of multiple system “swarm” style missions, as proposed for the Orbital Polar Resource Explorers DRM scenario.

Investments in architecture studies may well be required. There is a tradeoff between distributed/centralized team control, particularly when dissimilar uncrewed systems are operating individual heterogeneous robots or when there are dynamic considerations.

Part IV: Findings

The Moon DRM team finds that the following actions and activities would facilitate implementation of the DRM scenarios described above:

1) Establish study teams to investigate the current use of autonomous navigation and hazard avoidance
    a) Leverage recent industry advances in autonomous navigation
    b) Assess current Technology Readiness Levels (TRLs) and identify shortcomings
2) Establish requirements for onboard analysis capabilities for conducting autonomy
    a) Examine the processing requirements to conduct navigation onboard and identify central processing unit (CPU), storage, and power requirements
    b) Study how to leverage the limited downlink opportunities in some mission scenarios
3) Identify hardware that can enable improved autonomy; examples include:
    a) Low-power LiDAR for hazard assessment

b) Sunlight-tolerant imagers with sunglasses, adaptive polarizers, partial sunshade, etc. to improve the dynamic range in extreme lighting environments
c) Low power and accurate IMUs for situational awareness

The investment in autonomous navigation not only has the ability to enhance and enable a long-lived rover as the one discussed in this report, but can also feed into the design of other missions that incorporate mobility. By identifying hazards and optimal traverse paths, the asset can overcome obstacles and not wait for human interaction. As we explore further into the solar system, the communication time increases and human involvement can substantially hamper progress, and in some extreme environments, the wait can even put the mission at risk. Additionally, the inclusion of autonomy in almost any form will increase the processing requirements of the onboard computer. It is essential that NASA test and develop new processors that can handle the increased load. This development should be carried out at various scales so that capable processors will be available for power-limited environments such as those encountered on small spacecraft as well as in more resource-rich environments.

Part V: Moon Design Reference Mission Team

The Moon Design Reference Mission team is comprised of:

Eric Dixon, Lockheed Martin
Terry Fong, NASA
Thomas Howard, University of Rochester
Zach Mank, Honeybee Robotics
Steve McGuire, University of Colorado at Boulder
Jeff Schneider, Carnegie Mellon University
Emerson Speyerer (Lead), Arizona State University

Other Contributors:

Sam Lawrence, NASA Johnson Space Center
Florence Tan, NASA Headquarters

Part VI: References

Documents cited:

Committee on Human Spaceflight, National Research Council. (2014). *Pathways to Exploration: Rationales and Approaches for a U. S. Program of Human Space Exploration*. Washington, D. C.: National Academy Press.

Gruener, J. E., & Joosten, B. K. (2009). NASA Constellation Program Office Regions of Interest on the Moon: A Representative Basis for Scientific Exploration, Resource Potential, and Mission Operations. *LPI Contributions*, *1483*, 50–51.

Haruyama, J., Hioki, K., Shirao, M., Morota, T., Hiesinger, H., van der Bogert, C., Miyamoto, H., Iwasaki, A., Yokota, Y., Ohtake, M., Matsunaga, T., Hara, S., Nakanotani, S., Pieters, C. M. (2009), Possible lunar lava tube skylight observed by SELENE cameras, *Geophys. Res. Lett.*, 36, L21206, doi:10.1029/2009GL040635.

Hiesinger, H., Head, J. W., Wolf, U., Jaumann, R., & Neukum, G. (2011). Ages and stratigraphy of lunar mare basalts: A synthesis. *Geological Society of America Special Papers*, *477*, 1–51. https://doi.org/10.1130/2011.2477(01)

Jawin, E. R., Valencia, S. N., Watkins, R. N., Crowell, J. M., Neal, C. R., & Schmidt, G. (2019). Lunar Science for Landed Missions Workshop Findings Report. Earth and Space Science, 6(1), 2–40. https://doi.org/10.1029/2018EA000490

Jolliff, B. L., Wiseman, S. A., Lawrence, S. J., Tran, T. N., and the LROC Science Team. (2010) Scientific return from systematic imaging of the constellation exploration sites: Compton-Belkovich example. Lunar and Planetary Science Conference, #2412.

Lunar Exploration Analysis Group. (2011). The Lunar Exploration Roadmap: Exploring the Moon in the 21st Century: Themes, Goals, Objectives, Investigations, and Priorities. Retrieved from http://www.lpi.usra.edu/leag/LER-Version-1-1.pdf

Lunar Exploration Analysis Group. (2018). *Advancing Science on the Moon* (LEAG Specific Action Team Report) (p. 69). Houston, TX: LEAG. Retrieved from https://www.lpi.usra.edu/leag/reports/ASM-SAT-Report-final.pdf

Mitchell, D. L., Halekas, J. S., Lin, R. P., Frey, S., Hood, L. L., Acuña, M. H., & Binder, A. (2008). Global mapping of lunar crustal magnetic fields by Lunar Prospector. *Icarus*, *194*(2), 401–409. https://doi.org/10.1016/j.icarus.2007.10.027

Morris, G., & Sowers, G. (2018). *Lunar Polar Prospecting Workshop: Report*. Space Resources Roundtable. Retrieved from https://isruinfo.com/public//docs/LPP_2018_final_report.pdf

National Research Council Committee on the Planetary Science Decadal Survey. (2011). *Vision and Voyages for Planetary Science in the Decade 2013-2022*. Washington, D.C.: The National Academies Press. Retrieved from http://www.nap.edu/catalog/13117/vision-and-voyages-for-planetary-science-in-the-decade-2013-2022

Robinson, M., Ashley, J. W., Boyd, A. K., Wagner, R. V., Speyerer, E. J., Ray Hawke, B., ... Van Der Bogert, C. H. (2012). Confirmation of sublunarean voids and thin layering in mare deposits. *Planetary and Space Science*, *69*(1), 18-27. https://doi.org/10.1016/j.pss.2012.05.008

Robinson, M. S., Thanga, J., Wagner, R. V., & Hernandez, V. A. (2014). Arne — Sublunarean Explorer (Vol. 1820, p. 3025). Presented at the Annual Meeting of the Lunar Exploration Analysis Group. Retrieved from http://adsabs.harvard.edu/abs/2014LPICo1820.3025R

Space Studies Board, N. R. C. (2007). *The Scientific Context for Exploration of the Moon: Final Report*. Washington, D. C.: National Academy Press. Retrieved from http://www.nap.edu/catalog/11954/the-scientific-context-for-exploration-of-the-moon-final-report

Speyerer, E. J., Lawrence, S. J., Stopar, J. D., Gläser, P., Robinson, M. S., & Jolliff, B. L. (2016). Optimized traverse planning for future polar prospectors based on lunar topography. *Icarus*. https://doi.org/10.1016/j.icarus.2016.03.011

Speyerer, Emerson J., & Robinson, M. S. (2013). Persistently illuminated regions at the lunar poles: Ideal sites for future exploration. *Icarus*, *222*(1), 122–136. https://doi.org/10.1016/j.icarus.2012.10.010

Spudis, P., & Lavoie, A. (2011). Using the resources of the Moon to create a permanent, cislunar space fairing system. In *AIAA SPACE 2011 Conference & Exposition* (p. 24). Long Beach, CA: American Institute of Aeronautics and Astronautics. https://doi.org/10.2514/6.2011-7185

Spudis, P. D. (2016). *The Value of the Moon: How to Explore, Live, and Prosper in Space Using the Moon's Resources*. Washington, DC: Smithsonian Books.

Strawser, D., Thangavelautham, J., Dubowsky, D. (2014) A passive lithium hydride based hydrogen generator for low power fuel cells for long-duration sensor networks. *International Journal of Hydrogen Energy*, 39, p. 10216-10229.

Thangavelautham, J., Strawser, D., Cheung, M., Dubowsky, D., (2012) Lithium hydride powered PEM fuel cells for long-duration small mobile robotic missions. *IEEE International Conference on Robotics and Automation (ICRA).*

Wagner, R. V. & Robinson, M., (2014) Distribution, formation mechanisms, and significance of lunar pits. Icarus. 237, p. 52-60.

Whittaker, R. W. (2014). *Exploration of Planetary Skylights and Tunnels*. Retrieved from https://ntrs.nasa.gov/search.jsp?R=20190001167

Moon Design Reference Mission Report Summary

The Moon is an ideal exploration target for humans and robotic explorers. The Moon is the cornerstone of planetary science and provides the foundation for our collective understanding of many planetary processes. Results of prior and ongoing missions have proved that the Moon is an attainable, interesting, and useful location to study—but also that there is still more to learn and explore.

The Moon is the most accessible target for resuming human exploration beyond low Earth orbit (LEO). The Moon's vast and accessible resources make it a critical enabling asset for any United States' activities beyond LEO. Future surface missions to the Moon will provide NASA with much-needed ground truth for orbital datasets, as well as increase capabilities for automation that will enhance future missions and enable exploration of extreme environments.

The Lunar Exploration Analysis Group (LEAG)—a community-based, interdisciplinary forum that NASA formed to provide input and guidance regarding Agency lunar exploration objectives—identified three themes that address Agency goals for future lunar exploration:

1. **Science**: Pursue scientific activities to address fundamental questions about the solar system, the universe, and our place in them.
2. **Feed Forward**: Use the Moon to prepare for future missions to Mars and other destinations.
3. **Sustainability**: Extend sustained human presence to the Moon to enable eventual settlement.

The Moon DRM team suggests three autonomous DRM scenarios with general applicability to a variety of lunar exploration scenarios.

DRM Scenario: Lunar Roving Explorer (A Long-duration, High-speed Rover)

The long-lived, high-speed rover is a surface-exploration mission designed to investigate hundreds of scientific sites over a 1000-km traverse during two Earth years. The goal of this mission is to use autonomous mobility to acquire scientific measurements over a diverse array of lunar geologic terrains, addressing many key Decadal Survey[1] and Lunar Exploration Roadmap[2] objectives.

DRM Scenario: Orbital Polar Resource Explorers

This mission archetype uses coordinated, small, distributed spacecraft to fly as low as possible (10-20 km) above the surface and survey potential lunar surface volatile deposits from orbit to provide preliminary scouting of resource sites.

DRM Scenario: Sub-lunarean Void Explorer

This mission archetype explores a sub-lunarean void autonomously, without user guidance; assesses the utility of the sub-lunarean environments for human habitation and shelter; and increases understanding of the history of mare volcanism. Both propulsive robotic spacecraft and advanced mobility systems are proposed.
These three DRM scenarios all require of autonomy that is not currently available. Advancements in autonomy technology are required for these mission scenarios to perform the following:

Autonomous Local Navigation: To enable this capability, the rover will have to collect measurements while in motion with remote-sensing systems (e.g., Light Detection and Ranging [LiDAR] and/or stereo cameras). The information gathered will be processed onboard to build a model of the surrounding environment. From the model, potential hazards will be identified and an optimal traverse path will be computed without interaction of human controllers or computational resources on Earth.

Adaptation: Adaptive autonomy builds on the autonomous navigation outlined above but enables a human monitor to adjust a traverse or measurement objectives based on new observations. This technology will enhance the capability and science return.

Coordination of Multiple Robots/Assets: If a large number of surface assets have a mobility component, it will not be possible to control and monitor them individually using the standard operation methods presently used for planetary rovers, particularly if interactions with human

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[1] National Research Council Committee on the Planetary Science Decadal Survey. (2011). *Vision and Voyages for Planetary Science in the Decade 2013-2022*. Washington, D.C.: The National Academies Press. [http://www.nap.edu/catalog/13117/vision-and-voyages-for-planetary-science-in-the-decade-2013-2022].

[2] Lunar Exploration Analysis Group. (2011). *The Lunar Exploration Roadmap: Exploring the Moon in the 21st Century: Themes, Goals, Objectives, Investigations, and Priorities*. [http://www.lpi.usra.edu/leag/LER-Version-1-1.pdf].

explorers are desired. Therefore, the network of assets will need to communicate and coordinate with each other autonomously to identify the objectives of each and ensure productive non-interference.

Planning and Coordination of Multi-robot and Human-robot Teams: Future human missions may use mobile robotic assets to help collect measurements and complete maintenance tasks around a lunar field station. As lunar in situ resource utilization technologies are developed and implemented, planning and coordination of multi-robot and human-robot teams will be required.

To enable autonomy in these DRM scenarios, advancements in the following supporting technology areas are required:

- LiDAR
- Stereo imaging and processing
- Cross-link communications
- Cooperative power sharing/distribution (wired, inductive, or beamed power transfer)
- High-capacity computing power capable of advanced onboard processing and modeling
- Machine-learning platforms/architectures
- Team-level localization
- Scheduling/planning in high-dimensional state spaces, with uncertain observations of environment and human performance, team actions, and shared beliefs
- Inertial Measurement Units (IMUs)

Investment in autonomous navigation can not only enhance and enable a long-lived rover like the Lunar Roving Explorer discussed above but can also feed into the design of other missions that incorporate mobility. By identifying hazards and optimal traverse paths, the asset can overcome obstacles without the need for human interaction. As exploration proceeds further into the solar system, communication time increases, and human involvement can substantially hamper progress; in some extreme environments, the wait can even put the mission at risk. Additionally, the inclusion of autonomy in almost any form will increase the processing requirements of the onboard computer. It is essential that NASA test and develop new processors that can handle the increased load. This development should be carried out at various scales so that capable processors will be available for power-limited environments such as those encountered on small spacecraft as well as in more resource-rich environments.

Findings

The Moon DRM team finds that the following actions and activities would facilitate implementation of the DRM scenarios described above:

1. Establish study teams to investigate the current use of autonomous navigation and hazard avoidance

    a. Leverage recent industry advances in autonomous navigation
    b. Assess current TRL levels and identify shortcomings
2. Establish requirements for onboard analysis capabilities for conducting autonomy
    a. Examine the processing requirements to conduct navigation onboard and identify CPU, storage, and power requirements
    b. Study how to leverage the limited downlink opportunities in some mission scenarios
3. Identify hardware that can enable improved autonomy; examples include:
    a. Low-power LiDAR for hazard assessment
    b. Sunlight-tolerant imagers with sunglasses, adaptive polarizers, partial sunshade, etc. to improve the dynamic range in extreme lighting environments
    c. Low-power and accurate IMUs for situational awareness