Lunar Surface Science Workshop (LSSW) Session V:
Science Enabled by Mobility

1. Overview

Session V of the NASA Lunar Surface Science Workshop (LSSW) was held on October 28th, 2020 via a virtually enabled conference platform to accommodate COVID-19 in-person meeting restrictions. The LSSW Session V theme focused on 'Lunar science enabled by mobility'. Specifically, the expressed purpose of the LSSW Session V was to solicit input from the R&D community as to how access to mobility and associated mobility systems (i.e. crewed/uncrewed, and robotic) might impact science return and exploration opportunities on the Moon.

LSSW Session V included Invited Presentations, and a series of Short Talks and e-Posters that were sourced from abstracts submitted by the community. To provide a meeting environment whereby specific topics could be explored and discussed openly by workshop participants, two breakout groups were organized; these were focused on the following topics:

1. Determine the scientifically enabling and/or enhancing capabilities of rover (semi-autonomous) mobility systems without crew carrying capabilities, and
2. Determine the scientifically enabling and/or enhancing capabilities of crewed/uncrewed mobility systems.

Appendix 1 provides details of the Session V agenda. In total there were 243 participants for the invited and short presentations; for the breakouts, there were 63 participants in group 1, and 61 participants in group 2.

2. Invited presentation summaries

This section provides a summary of the topics presented by the three LSSW Session V invited speakers. For more details regarding the short talks and e-poster presentations, please refer to the following links:

- Short presentations:
  - https://www.hou.usra.edu/meetings/lunarsurface2020/program/lunarsurface2020_virtual5_program5.pdf
- E-posters:
  - https://www.hou.usra.edu/meetings/lunarsurface5/eposterindex.cfm

2.1 Invited presentation 1

Topic: Crewed & Uncrewed Mobility Platforms
Presenter: Dr. Michael Gernhardt
Abstract link: https://www.hou.usra.edu/meetings/lunarsurface2020/pdf/6012.pdf

This presentation was focused on mobility systems that will enable astronauts to explore a greater range of the Moon, thereby leading to the enhancement of science return during human missions. Details of the NASA Lunar Terrain Vehicle (LTV), a human-rated, unpressurized rover, and the Habitable Mobility Platform (HMP), which is a human-rated, pressurized rover for a longer-term sustained lunar surface presence, were presented. Additionally, this presentation put forward that during inter-mission, uncrewed periods, the LTV and HMP could be used as telerobotic exploration assets to enable further scientific exploration and sampling of the Moon.

2.2 Invited presentation 2

Topic: Lunar science and exploration enabled by the NASA VIPER (Volatiles Investigating Polar Exploration Rover)
Presenter: Dr. Anthony Colaprete

This presentation was focused on NASA's Volatiles Investigating Polar Exploration Rover, or VIPER. VIPER would represent the first in situ resource mapping mission on another celestial body, and is planned for delivery to the lunar South Pole surface in late 2023 under NASA's Commercial Lunar Payload Services (CLPS) program. This presentation highlighted that mobility is of paramount importance to the mission as this will allow scientists to gain a more holistic and detailed understanding of the highly heterogeneous lunar landscape. Specifically, mobility enables the mission to map and characterize the lateral and vertical distribution and form of volatiles (such as water ice) on the Moon.

2.3 Invited presentation 3

Topic: Apollo perspective on future lunar mobility systems
Presenter: Dr. Jim Head

This presentation provided insights from the Apollo missions as a guide to why mobility is important for future Artemis exploration of the lunar South Circumpolar Region (SCR). The speaker highlighted the need for mobility as a means to optimize science return. The following were listed as examples of goals and opportunities that would benefit from mobility systems on the Moon: i) the scientific exploration of polar volatiles, ii) the scientific exploration of SCR geology and geophysics, iii) interpolation - being able to use mobility systems to gather data between astronaut traverse paths, iv) extrapolation - being able to use mobility systems to gather data beyond astronaut-only exploration radii.

3. Breakout group discussion summary

3.1 Breakout Group 1:

Determining the scientifically enabling and/or enhancing capabilities of rover (semi-autonomous) mobility systems without crew carrying capabilities.

For the purposes of this discussion, rover mobility was defined to include such engineering solutions as wheels, legs for walking or hopping, or flight. Mobility was seen as crucial to "getting to the interesting science on the Moon." That is, engineering constraints often drive landing site considerations towards sites that are flat, without any potential hazards; scientists, on the other hand, typically prefer sites that have access to geologic and other information, often found in outcrops, boulders, and other areas that would present hazards to a spacecraft. The ability to include rover mobility systems within future lunar missions will enable the engineering, operations and scientific communities to address and to accommodate safety concerns and science interest simultaneously.

The breakout discussion focused on articulating various science priorities that the participants deemed were enabled by rover mobility systems. These priorities included:

3.1.1 Exploration and scientific characterization of inaccessible or dangerous areas on the Moon. It is anticipated that this would help to mitigate and reduce risks for human crews prior to their exploration of such areas as undisturbed outcrops, pits, lava tubes, potential subsurface cavities, steep/dangerous slopes, rough, treacherous terrain (boulder fields, lava flows), and permanently shadowed regions (PSRs).

3.1.2 Systematic mapping and exploration (geochemical and geophysical; vertically and horizontally), particularly to understand spatial heterogeneity over a large area in a way that is slow, precise, repetitive, and/or repeatable. The heterogeneity of the lunar environment is greater than lander-scale, thus systematic measurements require mobility. Such observations might include mapping the distribution of volatiles, geologic units and small-scale maps, resources (ISRU), thermal gradients, and topography.

3.1.3 Mobile deployment and retrieval of instrumentation (seismometers, mass spectrometers, etc.).

3.1.4 Science amplification during a human mission, by autonomously or semi-autonomously (a) carrying out systematic and/or repetitive observations, sensor deployments, or other science-related activities that would otherwise require significant crew time; (b) scouting in advance of crew deployment, thus increasing efficiency if areas of potential interest can be identified in advance; or (c) making additional detailed follow-up observations post-crew departure.

3.1.5 Engineering science opportunities would include conducting unique experiments related to the mobility asset such as geotechnical observations associated with surface/robot interaction (e.g., wheel-soil interaction mechanics); evaluation of the geotechnical properties of geologic materials (e.g, regolith, rocks, volatiles, etc.); learning about failure modes and causes from the mobile robotic asset itself that can increase reliability for future exploration rovers; and examination of Human-Robotic Interactions (HRI) to improve and evolve operational systems for future missions.

Breakout group 1 also explored the following issues that were not necessarily science priorities for consideration, but rather broader topics to be further discussed in future workshops:

3.1.6 How much autonomy is required? Precise mobility, precise localization, and the capability to execute slow, repeatable operations are all required; the level of precision required will be dependent on the type of instrument. Full autonomy was seen as high-value for repetitive, monotonous tasks, while human-in-the-loop direct teleoperation might be used for other more refined and unique tasks. Note that this issue also arose in Breakout Session 2, and the findings there are consistent with these.

3.1.7 What traverse types (point locations, linear traverses, or area coverage) facilitate which science questions? This issue was considered beyond the general scope of the workshop, but deemed important by the participants for follow-on work. The participants recommended looking beyond point locations, such as linear and area traverse coverages and vertical accessibility; and using large numbers of robots to be a "force multiplier" to allow rapid coverage of a large area, in a systematic, repetitive survey (e.g., swarms, massively parallel spatial operations).

3.1.8 The participants suggested a ***follow-on workshop to identify robotic capability requirements that would support specific aspects of various scientific investigations***.

3.2 Breakout Group 2:
Determining the scientifically enabling and/or enhancing capabilities of crewed/uncrewed mobility systems.

The purpose of the second breakout session was to outline the highest priorities for mobility-enabled science using a crewed/uncrewed mobile asset. Specifically, the following questions were considered:

3.2.1 What surface science is enabled or enhanced by human-capable rovers, both during crewed missions and between crewed missions? Related questions include:

- What are the science objectives? How does mobility benefit these objectives?
- What science instruments could be mounted on the rovers to achieve the science objectives?
- How can we best make use of the Lunar Terrain Vehicle (LTV) or Habitable Mobility Platform (HMP) mobility systems for science, individually and together?
- What crew-portable instruments and/or tools are needed to achieve the science objectives?
- What are the resources (power, volume, data rate) that would be required for the desired science instruments?

3.2.2. Furthermore, the following anticipated availability of the LTV and HMP mobility systems to the forthcoming Artemis missions was provided to the breakout session 2 participants:

- Artemis 3:
    - No Lunar Terrain Vehicle (LTV) or Habitable Mobility Platform (HMP) opportunities
- Artemis 4+
    - LTV crewed science opportunities during crewed missions
    - LTV uncrewed science opportunities between crewed missions
- Artemis Base Camp (Foundation Surface Habitat + LTV + HMP)
    - for 30-day missions, 4 crew will likely be split with 2 in the Foundation Surface Habitat (FSH) and 2 in the HMP, with crew pairs swapping mid-mission
    - Habitable Mobility Platform (HMP) crewed science opportunities during crewed missions
    - HMP uncrewed science opportunities between crewed missions
    - LTV and HMP working in conjunction (crewed and/or uncrewed) opportunities

3.2.3 The discussion also focused on the types of capabilities the LTV and HMP mobility platforms (which were detailed during the first invited presentation of LSSW V by Michael Gernhardt) would ideally support in order to "get to the interesting science". The following is an overview of participant comments:

- The LTV and HMP mobility systems should have 100+km ranges so that they can be used to map extensively and comprehensively, and to move between and within various geological terrains and thermal environments. Science is most enabled by mobility at the scales of 100 m to multiple kms, regardless of location.
- Thought should be given to the "level of autonomy" of each capability on the LTV and HMP. Those tasks that might be repetitive (e.g., standard sequences of images; repeating instrument observations) could warrant a greater degree of autonomy versus those tasks potentially better conducted with human-in-the-loop teleoperation.
- LTV and HMP mobility systems should have robotic arms for uncrewed opportunistic sampling (opportunistic sampling was commonly practiced by the crew during the Apollo mission rover traverses).
- Ground Penetrating Radar (GPR) and Neutron Spectrometer capabilities should be standard payloads on all rovers
- Between crewed missions (i.e. inter-mission periods), the LTV(s) and HMP(s) should be leveraged for interpolation, extrapolation, and/or reconnaissance activities. During these inter-mission periods, it would be valuable to the science community to be able to carry out additional experiments that would be enabled by the LTV and/or HMP mobility systems.
- It would be valuable to enable the LTV and HMP mobility systems to deploy other smaller mobility systems. Utilizing small rovers in combination with larger rovers

could be useful for scouting, communication relays, mission planning, access to areas not trafficable by larger rovers, etc.

4. Summary of discussion input

Overall, the participants collectively agreed and emphasized that the availability of mobility systems not only extends the physical range of exploration, but also the intellectual range of our scientific understanding of the Moon. In particular, building geological context, within which individual sample data can be interpreted and understood, is critical and will be most beneficial through the ability to move across the lunar terrain on the order of 100's of kilometers.

The participants articulated that the following science-driven exploration activities would be enabled by mobility:

1. Scouting of scientifically interesting areas in advance of crew to determine the accessibility, benefit, and risk factors associated with astronaut scientific exploration,
2. Transport of crew, science instruments, tools, and samples further and more efficiently than is achievable by crew alone,
3. Exploration of scientifically interesting areas that are inaccessible to astronauts,
4. Autonomous and/or teleoperated systematic mapping (with various instrument payloads) that would would be tedious and time consuming for astronaut crews,
5. Conducting unique geotechnical experiments enabled by the range and payload carrying capabilities of the mobility assets, and
6. Deployment and retrieval of instrumentation arrays across large areas.

5. Forward Steps

Workshop participants recommended that follow-on meetings and activities be organized to discuss and sort through details related to the topics that were presented and discussed during LSSW V. The following is a list of future work efforts that were suggested by LSSW V participants:

- With community input, construct a matrix that builds upon the Artemis III SDT report (in particular section 7.3; https://www.nasa.gov/sites/default/files/atoms/files/artemis-iii-science-definition-report-12042020c.pdf) to provide the details of:
    - Specific lunar science objectives, hypotheses, experiments, instruments, activities and tasks that are enabled by specific crewed/uncrewed and rover mobility assets,
    - The traverse range requirements (e.g. 100m, 10-km, etc) for each of those science objectives,
    - The engineering and operations parameters for the mobility assets (e.g. rover slope angle capability range, temperature range of areas of interest and time required in hot and cold areas, etc) that must be considered in order to address those science objectives,

- Whether these science objectives require crewed, and/or uncrewed mobility systems to be accomplished,
- If uncrewed, what type of mobility system would be appropriate for each science objective (e.g. LTV, HMP, smaller robotic rovers, combination of these systems, etc),
- If uncrewed, during what mission period the mobility system would be active (i.e during crewed missions, between crewed missions, both).
- The level of autonomy and/or teleoperation required to meet sampling rates, sampling procedures, etc.

Appendix 1. LSSW Session V Program; Breakout sessions were facilitated by S. Chappell, J. Hurtado, E. Bell, and L. Jozwiak

Lunar Surface Science Virtual Workshop #5
Science Enabled by Mobility
October 28, 2020

Program and Abstracts
All times are Eastern Daylight Time (EDT) (UTC -4)

Times (EDT)	Presenters	Title
		Opening Remarks and Invited Talks
12:00 p.m.	Aileen Yingst, Darlene Lim	Welcome Remarks
12:10 p.m.	Michael Gernhardt	*Crewed and Uncrewed Mobility Platforms — Science Opportunities for Future Lunar Exploration* **[#6012]**
12:30 p.m.	Anthony Colaprete	VIPER Lunar Rover: Lunar Science Enabled Through Mobility **[Invited]**
12:50 p.m.	Jim Head	Apollo Perspective **[Invited]**
1:10 p.m.		BREAK
		Short Talks
1:20 p.m.	David Kring	*Lunar Mobility Strategies, Trade Studies, and Mission Simulations* **[#6007]**
1:30 p.m.	Pascal Lee	*Science in Extreme Environments on the Moon and Its Mobility Requirements* **[#6015]**
1:40 p.m.	Mark Robinson	*Intrepid: Long Range Lunar Rover Enabling Science and Exploration* **[#6016]**
1:50 p.m.	Pamela Clark	*Utilizing Mobile Instrument Suites to Meet High Priority Lunar Science Objectives* **[#6005]**
2:00 p.m.	Mason Bell	*Construction of Lunar Radio Astronomy Telescopes Leveraging Low-Latency VR/AR Teleoperation* **[#6008]**
2:10 p.m.	Kirby Runyon	*Science Enhancements at Amundsen Crater from Mobility* **[#6009]**
2:20 p.m.		BREAK
2:30 p.m.	Matthew Atwell, Mark Robinson	*Deployable Robotic Hopper for Versatile Lunar Science Access* **[#6011]**
2:40 p.m.	Andrew Gemer	*Lunar Science Mobility as a Service: The Lunar Outpost Mobile Autonomous Prospecting Platform (MAPP) Rover* **[#6006]**
2:50 p.m.	Michael Provenzano	*Mobility as a Service for Lunar Payloads* **[#6002]**

Times (EDT)	Presenters	Title
		Lightning Talks with Virtual Posters To view all submitted e-posters: **View E-Posters**
3:00 p.m.	Michael Walker	*Mixed Reality Interfaces for Mobile Lunar Surface Robots* **[#6013]**
3:02 p.m.	Kaizad Raimalwala	*Science Autonomy on a Lunar Micro-Rover to Maximize Return* **[#6014]**
3:04 p.m.	Alian Wang	*Wheel Science: 3D Survey for Lunar Volatiles* **[#6010]**
3:06 p.m.	Berkay Kars	*Future Earth-Moon Transportation Methodology* **[#6001]**
3:08 p.m.	Midhun Menon	*URSSA: A Simulator for Lunar Surface Telerobotics Research* **[#6004]**
3:10 p.m.	Sungsoo Kim	*Light Field Cameras for Dust Particles On and Near the Lunar Surface* **[#6003]**
3:12 p.m.		BREAK

Times (EDT)	Presenters	Title
		Break Out Groups
3:15 p.m.		Break Out Groups —Discussion Part 1 Group #1: Science Enabled by Semi-Autonomous Robotic Rovers Group #2: Science Enabled by Uncrewed (But Crew-Capable) Rovers
4:15 p.m.		BREAK
4:30 p.m.		Break Out Groups — Discussion Part 2 Group #1: Science Enabled by Semi-Autonomous Robotic Rovers Group #2: Science Enabled by Uncrewed (But Crew-Capable) Rovers
5:00 p.m.		Break Out Groups — Report Out
5:30 p.m.	Aileen Yingst, Darlene Lim	Final Thoughts, Closing Remarks, Next Steps
5:45 p.m.		ADJOURN