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Introduction: Field geological exploration conducted on the lunar surface will be the keystone for addressing the open scientific questions raised at this meeting. Executing these activities will be complex and expensive, regardless of whether the agent conducting the exploration is human or robotic. Therefore, it is critical that the next steps in lunar scientific exploration be understood in the terms of the goals and preparations required, including crew selection. This includes the operational approaches necessary to conduct productive and efficient surface science operations, the hardware and training necessary to acquire the appropriate samples and data, and the experience and training required of those involved, both crewmembers on the Moon and operations personnel on Earth. Each of these elements needs to be integrated into mission design, planning, training and execution from the beginning, such that science is an integral part of the operation, not a late-stage add-on.

Basic Premise and Applications to This Conference: Our premise is that for each open science question, there is a limited range of possible solutions that will provide the desired exploration efficiency, control costs, manage the operational risk to human and robotic crewmembers, and allow for unexpected discoveries. Early analysis of operational approaches and requirements appropriate to each question will identify whether human or robotic assets will improve the chances for mission success. Failure to identify the appropriate approaches will likely lead to a mismatch of the mission assets applied, and will also lead to increased costs and risk by developing assets that are either insufficient to meet the science objectives, or are over-designed and more complex to operate. The key concept is that *we should never send a robot to do a human's job, and or send a human crewmember to do a task more efficiently executed by a robot*. An effective way to analyze these options is to define, for any given science question, a set of limited, straightforward mission objectives. Accomplishment of these objectives can be aided by providing as much flexibility as possible to the individuals responsible for mission execution.

Human and Robotic Agent Attributes: The two end member agents for conducting surface science operations are humans and robots, either operating in isolation or in tandem. Each agent has both strong points and limitations, and *neither* agent is appropriate for *all* exploration science operations tasks. In particular, experience has shown that duplicating the capabilities and efficiencies of experienced field geologists in a robotic agent would be more costly than a human mission. The use of human explorers will always be a necessary component of extensive and successful lunar surface exploration

Human agents with an extensive foundation of experience and training provide the most flexible, intuitive and efficient capability to dealing with complex scientific and operational situations, such as planning a detailed strategy for sampling/surveying, analyzing a complex geological locality, post-sample collection analysis, or implementing solutions to unexpected challenges and discoveries. Human explorers are significantly better at developing exploration strategies and modifying those strategies in real-time [1]. Hodges and Schmitt [1] adapted the concept of flexicution [2], [3] to illustrate how field geologic mapping is executed in a terrestrial setting. The value of flexicution has been illustrated in the continued evolution of understanding of the geology of the valley of Taurus-Littrow as the original field geological observations and sampling are continuously integrated with 45 years of sample analysis and remote sensing data [4]. Geologic mapping, based on remotely-gathered data and modified by real-time planning during lunar exploration, will be a critical human task for understanding complex scientific problems on the Moon and Mars. While not all lunar science problems require geologic mapping, developing a sufficient grasp of the geographic and stratigraphic setting of returned samples will establish the geologic context necessary for post-mission analysis of samples and data, and will be critical for answering many of the scientific problems identified at this meeting.

In contrast, robotic agents work best in the conduct of routine, repetitive activities during preand post-mission investigations – robots do not get bored, they can be designed to repeat the same procedure identically as many times as required, they continue to function as long as they have operational resources such as power and working mechanisms, and they are engineered to be fault tolerant. Robots can also be designed to operate in environments would significantly increase risks to human crewmembers, although more challenging environments will likely increase costs and/or add launch mass. Many of the open lunar science problems can be addressed more efficiently by robotic science missions executed at multiple localities, rather than through a single large-scale development of a single surface locality. Using robotic agents for operations appropriate to their capabilities will result in recovery of samples and scientific data that might otherwise be difficult and expensive to acquire by human crewmembers (e.g, recovery of samples from steep walled craters).

The integration of human and robotic exploration can best be achieved through the use of precursor and post-cursor robots and multi-use roving vehicles. Precursor robots can assist greatly in exploration planning, and initial site identification and characterization, while post-cursor robots can follow-up on questions raised by human discoveries or by continuing sample and data acquisition conducted after crew departure. The use of robotic field assistants has not been a normal procedure in terrestrial exploration and their use has so far remained conjectural for lunar and planetary exploration. The present generation of robots involved in planetary exploration (e.g., the Mars Science Laboratory, the Yutu series of Chinese rovers) move very slowly in contrast to human planetary exploration vehicles and surface crewmembers. A comparison of traverse times between the Apollo Program and the Mars Exploration Rover (MER) is illustrative: it took the Apollo 17 crew three days to put ≈28 km on the Lunar Roving Vehicle odometer, while it took MER Rover Opportunity over 3000 Martian sols to accumulate the same mileage [J. Head, personal communication, 2015]. Clancy [5] correctly stated that humans are exploring Mars, not robots, but the speed of our present approach to cyclic operations makes the speed of robotic exploration extremely slow when compared to the Apollo Program experience. The relatively close proximity of the Moon will reduce cyclical robotic operation times compared to Mars robotic operations, but the present family of planetary robotic assets is not capable of traversing the lunar surface at the speeds that can be achieved by human explorers. Integration of human crewmembers and robots as complementary field partners remains an illusive goal, but one that may be solved with continued engineering research and development.

Training and Equipping Human Explorers: Successful lunar scientific exploration in the next decades will require cross-trained crewmembers with backgrounds as pilots, engineers and scientists. The success of the Apollo program has shown both that crewmembers from multiple disciplines can function as a successful integrated crew, provided the appropriate training is undertaken prior to each mission. For Apollos 15-17, this included extensive (>1000 hours) [6] [7] of science training in relevant field localities to hone observational and EVA skills within a specific mission context. Future human crewmembers will require similar levels of training to be competent geologic explorers, regardless of their original technical training and experience. This is a particularly critical feed-forward activity to the exploration of Mars. In recognition of this requirement, NASA has begun training each new astronaut class in the fundamentals of field geologic observations, starting with the 2009 Astronaut Class.

In addition to the usual complement of simple hand tools (hammers, rakes, scoops, core tubes, drills) carried on Apollo, the advent of portable analytical equipment has the potential to greatly enhance in-situ sample analysis and collection quality, reduce returned sample mass, and assist on-going planning of future operations. However, these tools must be able to provide meaningful analytical data within the time context of a human mission – extensive integration times will limit effective use by human agents, and make them more applicable to use by robotic agents or in habitat laboratories. Continued testing and revising of operational concepts for the use of these tools has the potential to significantly change the real-time science return from human exploration missions.

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