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REQUIREMENTS ASSESSMENT AND OPERATIONAL DEMANDS FOR A RESOURCE MAPPING ROVER MISSION TO THE LUNAR POLAR REGIONS

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ABSTRACT

A preliminary set of requirements for a robotic rover mission to the lunar polar region are described and assessed. Tasks to be performed by the rover include core drill sample acquisition, mineral and volatile soil content assay, and significant wide area traversals. Assessment of the postulated requirements is performed using first order estimates of energy, power, and communications throughput issues. Two potential rover system configurations are considered, a smaller rover envisioned as part of a group of multiple rovers, and a larger single rover envisioned along more traditional planetary surface rover concept lines.

KEYWORDS: robot, rover, lunar, drilling, prospecting, water, ice, energy, power, thermal

INTRODUCTION

The recent discovery and confirmation of extensive hydrogenous material in the polar regions of the Moon by the Lunar Prospector spacecraft has re-ignited interest for a return to the Moon as a base for exploration. If this hydrogenous material is in the form of water ice or ammonia ice, it has enormous ramifications for a self-sufficient base and for an eventual permanent human presence on the surface of another world. The presence of hydrogen makes feasible low-cost round-trip transportation from the surface of the Moon to Low Earth Orbit. It also enables a lunar base to become highly self-sufficient in a short period of time.

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DISCLAIMER

There are two primary possibilities for the location of a permanently manned lunar base: Fra Mauro near the equator or at the lunar poles if water ice or ammonia ice is present. However, in order to perform site selection, more information is necessary on the size, location, extent and availability of resources, particularly water at the poles. Because portions of the lunar polar regions are permanently shadowed, some dramatically increased level of hydrogenous material is available. However, because these regions are permanently shadowed, there is a limit to the available data from orbit. Consequently a direct measurement surface explorer mission is required, and robotic rover technology appears to offer a feasible technical approach.

The lunar polar regions represent some extreme conditions with which a robotic explorer must contend. The purpose of this paper is to identify mission requirements and operational demands for a resource measurement robotic lunar surface rover, beginning from the standpoint of the mission's science goals and to assess those requirements and demands in terms of how they drive the system's engineering design. The objective is to attempt to determine what is realistically possible to achieve with various general concepts for conducting the exploration mission. In particular, since a collective of cooperative robots is currently an envisioned mission scenario in the minds of more than a few researchers, an assessment of robot system concepts utilizing multiple small simple cooperating rovers versus one larger highly capable rover will be performed to determine which approach is more practical for this mission. This comparison will be done primarily in terms of the estimated energy and power requirements to accomplish various tasks on the lunar surface, vehicle mobility considerations, and system redundancy issues. This information may be used for planning purposes for a future lunar resource mapping mission to one or both lunar poles.

MISSION REQUIREMENTS

The science goals for a mission to the permanently shadowed regions at the lunar poles are primarily to determine what, if any volatiles are present in the soil that could account for recent data that appears to signal excess hydrogen present in the soil [1]. This has been hypothesized to perhaps be either water ice or ammonia ice, and since it may reside at significant depths below the surface core sampling is likely to be required. A secondary science goal is to return data regarding the presence and quantities of various elements in the lunar regolith down to a depth accessible via excavation. Lastly, the return of video images from the rover will be an added bonus source of information about both the local surface conditions and the core samples. Table I enumerates specific goals outlined by the envisioned user, a Principal Investigator-scientist with considerable experience in space missions but minimal experience in robotic system design.

With regard to system complexity and technical risk, one firm requirement from Table I is that the system be teleoperated from an Earth-based ground site with minimum on-board computing. Implicit in this requirement is the assumption that teleoperation requires less compute power than semi-autonomous or autonomous operation. The rover must therefore be able to communicate with Earth either directly from the rover position or through a communications relay, in a continuous fashion. The communications relay may be accomplished through either the lander bus or a small satellite in lunar orbit. If performed using communications relay satellites in lunar orbit, continuous operation implies that at least two satellites be placed 180 degrees out phase in lunar polar orbit.

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Obviously, the lander bus must also be capable of communicating with Earth from the landing site, either directly or through an orbiting relay satellite. Since this mission will be operating in perpetual shadow some provision for either lighting the scene or using a thermal imager to enable teleoperation will be required. Teleoperation of a robotic lunar rover from Earth with the typical 2.7 second round-trip communications time delay was demonstrated by the Soviet space program in 1972 [2].

Table I. Mission Requirements as Originally Posed by Principal Investigator

MAJOR CATEGORY A Rover system: Design through launch phase:
1. Be of robust design and capable of meeting technical requirements as described below.
2. Minimize cost and schedule in performance of mission requirements.
3. Complete system testing prior to launch.
4. Minimum mass for completion of the mission.
5. Rover is to be operated from ground site with absolute minimum on-board computing.
6. Rover must be compatible with lunar lander.
7. Rover must fit in a low-cost launch system.
8. Rover must be able to communicate with either directly from rover position or through an orbiter.
9. Lunar lander bus must be capable of communicating with Earth from landing site, either directly or through another satellite.
MAJOR CATEGORY B: Rover system: Launch through Final Descent and Lunar Landing Phase:
1. Rover system must be capable of depositing small probes on the lunar surface during roving.
2. Rover must be capable of providing positioning data so its position can be accurately determined.
3. Rover must be capable of transmitting real-time and stored data to earth and/or orbiting satellite.
4. Rover system must be capable of multiple sorties into permanently shadowed region of the polar region for data and sample collection.
5. Operating in a permanently shadowed region of the Moon for a minimum of 6 months continuous operation.
6. Traversing in this region (during) extended free roaming at a minimum speed of 5 km/hr without performing any in-situ sampling activities.
7. Providing real-time 6-8 bit gray scale 256X256 video; frame rate 1-5 frames/sec
8. Performing drill samples to depths of 3-4 meters at the rate of two drill holes/24 hour day on available rover power
9. Recovering drill samples and performing the following functions: heating sample to 70C and 400c in separate steps for detection of volatiles. Detecting the presence of the following substances and quantities: U, Th, K, Fe, Ti, Mg, Si, O, Ca, Al, N and C and other substances.
10. Providing video transmission of core samples.
11. Excavating samples in bulk to a depth of 2 meters and performing analyses on the excavated samples at a rate of one per 24 hours day on available rover power.
12. Transmitting data to ground station

REQUIREMENTS ASSESSMENT

An initial assessment of the mission requirements indicates some basic conflicts exist. The mission science goals require core sampling and processing, surface excavation to a significant depth, real time communications, and reasonably long teleoperated traverses at a significant velocity with a 2.7 second round trip time delay, all while operating in a permanently shadowed region at very low ambient temperatures. Furthermore, the programmatic mission requirements include low cost and high robustness. Low system cost and a high degree of robustness are very nearly mutually exclusive in the spacecraft

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field, since making a robust system with high reliability has typically been accomplished through expensive testing and qualification procedures for all components. Cutting costs in recent NASA Discovery class missions has been accomplished in most cases by allowing a higher acceptable level of risk for component failure and reducing the qualification and testing requirements.

There are a variety of mission scenarios that could conceivably accommodate the stated requirements, however two fundamental criteria that will drive virtually any mission scenario are the energy and power requirements necessary to carry out the basic mission. Major system-level energy and power issues that arise when considering a lunar polar surface mission include communications, power/energy density, mobility, and thermal management. These are briefly discussed below.

Communications

Communication with a rover at the lunar pole is extremely problematic since Earth would appear very low on the horizon, if at all. This implies some form of communications relay will be required, either via a small satellite in lunar orbit or perhaps a device located on a high elevation situated such that it has a simultaneous view of Earth and of the rover's area of operations in permanent shadow. In either case, additional resources in terms of available launch mass will be required to address this issue. The addition of one or more satellites delivered to lunar orbit increases the overall system complexity, and in very simplistic terms tends to reduce overall system robustness by increasing the number of possible failure points. The lunar poles have never been visited by any surface landers, and since they have only recently been surveyed from lunar orbit, knowledge of the terrain at high spatial resolution is limited. This lack of detailed knowledge makes mission planning difficult, since from the previous discussion it is apparent that placement of the rover and any associated surface based communications relay station(s), i.e. the lander, will be critical for mission success.

Bandwidth and transmit power requirements will vary according to antenna selection at both the lunar and Earth end of the link, however using some typical values based on a 10 kilobaud data rate at 1.0 GHz frequency the estimated electrical requirements to the transmitter is approximately 5 watts. This number can easily vary by a factor of 2 depending on antenna selection, transmitter efficiency, and signal to noise performance. Assuming 24 hour per day communications with the vehicle from Earth by making use of communication relay satellites in Earth orbit means that communications energy requirements over the entire mission amount to approximately 80 MJ.

The Earth-Moon-Earth round trip communications time delay precludes high speed teleoperation unless some onboard autonomy is employed to avoid collisions. The 5 km/hr speed requirement will result in the vehicle moving a 'look-ahead' distance of 3.7 meters every 2.7 seconds. This is the distance that the vehicle will move between the instant the teleoperator perceives a potential hazard condition and the instant the vehicle receives the command to correct its trajectory. Any hazards existing within that range in front of the vehicle cannot be avoided by teleoperation alone. If a rule of thumb stating that the maximum hazard zone in front of the vehicle be no more than 1 or 2 vehicle lengths is assumed, then for vehicle sizes from 0.5 to 1.0 meters long a maximum safe operating speed will be between 0.6 and 2.5 km/hr. This speed may be significantly

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increased through the addition of even rudimentary onboard obstacle detection, effectively cutting the closed loop response time to less than one second. In this case the maximum safe operating speed may be increased to as much as 2.5 km/hr, based on experience with terrestrial rovers and a simulated 3.0 second time delay with significant maneuvering.

Energy and Power for Mobility

Experimental data [3] on energy and power characterization for terrestrial rovers show that the energy cost for a wheeled electric vehicle using conventional planetary gearhead drives, normalized on a "per meter traveled, per kilogram vehicle mass" basis is approximately 3.5 J/m/kg. This is based on data taken at an average velocity of approximately 2.5 km/hr while traversing moderately rolling natural terrain and neglecting any major elevation changes. Assuming an average speed of 2.5 km/hr, a mission duration of 6 months, and a duty cycle of 50% (leaving 50% for sample acquisition and conducting sample analysis), the rover would require approximately 19 MJ of energy per kilogram of rover mass just for mobility. To put this number into perspective, gasoline has an energy density of 50 MJ/kg thermal energy. Incorporating typical thermodynamic efficiencies this drops to 15 MJ/kg mechanical energy. On the moon, one would need to carry an oxidizer along leaving about 2 MJ/kg. The best batteries available are about 1 MJ/kg. Although the instantaneous power requirements for the rover will greatly depend on the terrain conditions, an average value for just the mobility system can be estimated by dividing the total energy by the projected driving time of ~2200 hours, yielding a value of approximately 2.5 W/kg of rover mass. Experience with electrically powered terrestrial rovers such as the RATLER™ [4] shows this value to be a very reasonable estimate of average power for cruise traverses. Peak power values during maneuvers in very rough terrain can be as much as an order of magnitude higher for periods of a few seconds.

Core Sample Drilling

Since the primary mission science goal is to determine the source of excess hydrogen apparently present in the Lunar Prospector data, the rover's primary function should be to cover a large area when traversing and to take core samples from 2 to 4 meters deep at regular intervals. Previous lunar missions obtained core samples down to approximately 1 meter using a drive tube and a hammer, and down to approximately 3 meters using a rotary coring bit [5]. Since the desired sampling depth on the proposed mission is 2 to 4 meters, a rotary drilling technique will be assumed.

At an average speed of 2.5 km/hr and a mobility duty cycle of 50%, the rover would traverse an average of 30 km every 24 hour period. If 2 core drill samples are taken every 24 hour period, then the samples would be approximately 15 km apart. The total distance traversed is estimated to be approximately 5500 km, so that at a spacing of 15 km between drill holes there would be a total of approximately 365 core samples taken. If spread over a square region on the lunar surface, this would be an area approximately 285 km on a side, or subtending approximately 9.5 degrees of arc using a nominal (spherical) lunar radius of 1738 km, a total area of approximately 81,000 square km or 0.2% of the lunar surface.

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Drilling a core sample in 1/6 g and a hard vacuum presents some challenging problems. First, the drilling rate is approximately a linear function of the applied axial force, which in turn is usually limited to the static weight of the drill stem and attached drill bit [6]. One potential approach to overcoming this limitation would be to use a dynamic technique, either by imparting a reciprocating motion to the drill string to increase the instantaneous applied force at the drill face, or by imparting a shock-impact load periodically along the drill string axis in the manner of a conventional hammer drill. Improving the coupling between the rover and the lunar surface via deployable cleats thereby increasing the potential reaction torque available could also be advantageous.

Second, the use of a cutting fluid as is typically done in terrestrial drilling operations to clear cuttings from the bit and to both cool and lubricate the bit and stem is highly problematic in the lunar environment. Although drilling techniques for the lunar surface have been proposed which do employ fluids [7], the additional mass and power requirements to employ such a system tend to reduce its desirability for this application. Other reasons for discounting this technique include the need to carry a consumable resource (the fluid itself), as well as the potential for direct contamination of the core sample and indirect contamination of the rover's sensors. Some other method for removal of drill cuttings will be required, probably a mechanical Archimedes' screw or similar device incorporated into the drill string assembly as was done on the Apollo 15 through Apollo 17 missions [5]. Cooling of the bit must be accommodated via a combination of conduction into the drill face and by removal of the 'hot' cuttings.

The acquisition of up to 2 core samples per 24 hour period, each of which could be from 2 to 4 meters in length presents problems of its own. Over the course of a six month mission the rover will have acquired approximately 1100 linear meters of core sample material, massing approximately 800 kg assuming an average density of 1.5 g/cm^3 [8] and a core diameter of 2.5 cm. Carrying these samples back to a lander for processing wastes precious time and resources better used for covering more new ground, so it is likely that the core samples will be processed on the rover and then either discarded or cached for later retrieval. This scenario requires the rover to carry the equipment required to process the samples, further increasing the rover's total mass. In order to avoid cross contamination of subsequent samples, either each sample will either have to be isolated in its own container/wrapper within the drill string, or it may be required to flush or clean the core drill hardware between drill sites.

In order to estimate the energy and power requirements for drilling the core samples, some assumptions about soil mechanics must be made. Although data on lunar soils exists for the equatorial regions [9], correlation to soils in the permanently shadowed polar regions of interest is not obvious due to the lack of a solar-induced thermal cycle. In the absence of hard data to the contrary, the assumption made for the following discussion is that the shadowed region soils' bulk properties are not substantially different from lunar equatorial soils.

In estimating the energy and power requirements for a purely rotary drilling technique, the total torque required to overcome the soil's shear strength and just begin to turn the drill bit was estimated using the relation:

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$$T = \int_{r\_inner}^{r\_outer} \int_0^{2\pi} \tau * r^2 d\theta dr \quad (1)$$

where:

T = torque
r_inner = inner radius of core drill bit
r_outer = outer radius of core drill bit
τ = soil shear strength
r = radial distance to cutter surface from rotation axis

Lunar regolith shear strength has been measured to be approximately equal to the applied normal stress [10]. Using an average regolith shear strength of 150 kPa based on a 100 kg rover, an outer drill diameter of 2.54 cm and drill bit wall thickness of 1 cm, the total torque required is approximately 4.5 Nm. Allocating 25% of the total duty cycle to drilling core samples, each core sample must be drilled in no more than 3 hours, requiring a minimum vertical feed rate of approximately 22 mm/minute (0.87 inches/min). Depending on the soil conditions and the cutter efficiency, the average instantaneous power required is estimated to be approximately 400 watts. Over the course of the entire 6 month mission this will total approximately 1600 MJ of energy. The motorized drill used on Apollo 15 was specified at 21.0 amps and 18.5 volts DC yielding a power figure of 388.5 watts [11], which agrees rather well with the average power estimated earlier.

Thermal Energy Management

Since the rover will be operating in permanent shadow, the surroundings will likely be extremely cold and as a result very large temperature gradients will be available to drive the heat transfer processes. Since the lunar environment is essentially a hard vacuum, the thermal energy balance for the rover will depend heavily on both the radiative properties of the rover's external surface to the surrounding lunar environment and the conduction properties of the locomotion mechanism to the lunar soil.

Using a simple steady state, 1-D thermal plane-wall model for the rover's main enclosure, a rough estimate of the heat transfer performance may be obtained. Assuming the rover's internal temperature at 273 K and the ambient lunar surroundings at 43 K [12], heat transfer is via conduction through the walls to the outer surface and then via radiation from the outer surface to the surroundings. Since the rover is assumed to be operating in perpetual darkness, zero solar-induced energy gain is assumed and the absorptive/reflective properties of the rover's outer surface are ignored for this analysis.

As shown in Figure 1 below, the heat transfer rate per unit area from the rover's main enclosure can be maintained at or below 50 watts/m^2 with the proper combination of conductivity and emissivity properties of the wall itself. For conductivity values in the 0.001 to 0.01 watts/m*K range typical of high grade insulation materials such as metal foil/glass blanket multilayer composites, the emissivity of the outer surface plays very little part in heat transfer. Whereas, for conductivity values in the range from about 0.05 to 10 watts/m*K and above the emissivity dominates the heat transfer process for the internal and external temperatures stipulated above. Calculations of the estimated heat transfer from the wheels to the soil via conduction show that these losses are on the order of 2% to 10% of the radiated losses.

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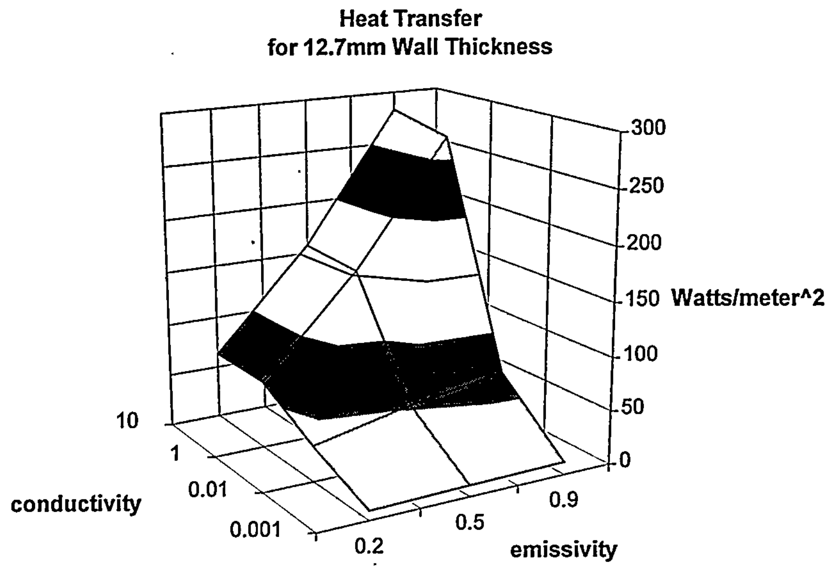

Figure 1. Heat transfer as a function of outer surface emissivity and wall conductivity of the main body enclosure/structure. Assumes rover internal temperature at 273 K, outside surroundings at 43 K.

Although thermal management of the rover system in a permanently shadowed region may in fact be somewhat less challenging than in an equatorial region since no solar energy gain will occur, the use of solar photovoltaic panels for recharging is obviously a problem.

The rover's total energy consumption budget for a 6 month mission is summarized in Table II. Note that two rover configurations are shown. One is for a small 20 kg class machine that would be part of a group of simpler cooperative rovers, and the other is for a 100 kg class machine envisioned as a single more capable rover. Also note that a range of thermal energy and power values are given, which correspond to a radiative heat flux range from 10 to 50 W/m^2 using the curve shown in Figure 1.

Table II. Energy Consumption Budget

Item	**Energy**	**Average Power**
Comm.	80 MJ	5 W
Drilling	1600 MJ	400 W
Mobility	*19.2 MJ/kg* 20 kg rover: 435 MJ 100 kg rover: 1920 MJ	20 kg rover: 50 W (200 W peak) 100 kg rover: 250 W (1000 peak)
Thermal	20 kg rover: 130 to 650 MJ 100 kg rover: 512 to 2500 MJ	20 kg rover: 200 to 1000 W 100 kg rover: 780 to 3800 W
Total:	**20 kg rover: 2100 to 2700 MJ** **100 kg rover: 4000 to 6000 MJ**	

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Energy Sources

Since the rover will be operating in perpetual darkness the use of solar photovoltaics as an energy source is not an option. The rover must therefore carry its entire energy supply along, or else make periodic return trips to the lander to recharge/refuel. Although fuel cells are a proven technology in spacecraft and the lander could potentially be used as a refueling station for the rover, the practicalities of automated or teleoperated refueling of the rover present significant technical challenges. It would appear that batteries provide the simplest option for providing for the instantaneous power required, and it simply remains to determine how to extend the total energy capacity to cover the entire mission duration. If an isotopic energy source can be used as an energy reservoir to recharge batteries then it is possible to carry the entire energy supply required for the rover mission. Of course, an isotopic source that has the instantaneous power capacity to meet operational requirements and the total energy capacity for the total mission would eliminate any need for batteries.

Primary batteries can typically provide energy densities on the order of 1 kJ/gm, whereas isotopic sources such as Thulium-170 can provide as much as 34 MJ/gm total energy and 246 W/gm of power [13]. Conversion from isotopic sources to electric power is only about 10% efficient, so for electrical systems the available energy density is approximately 3.5 MJ/gm and the power density is approximately 24.5 W/gm. The remaining 30.5 MJ/gm is available as thermal energy to be used to keep the rover warm.

CONCLUSION

Based on the energy estimates developed previously for drilling, thermal, and mobility uses, the total energy required to accomplish the surface mission objectives should be approximately 2100 MJ to 2700 MJ for a small 20 kg class rover, and should be in the range of 4000 MJ to 6000 MJ for a larger 100 kg class rover. For the smaller class of rover, the worst case allots approximately 24% of the total energy for thermal use and for the larger class of rover the figure is approximately 40%. This implies that for a system employing Thulium-170 as a primary energy source, a small 20 kg class rover would require approximately 200 grams (0.9% of total rover by mass) of material to accommodate the total energy requirements and provide as much as 5 kW of instantaneous power capacity. Similarly, a 100 kg class rover would require approximately 667 grams (0.7% of total rover by mass) of Thulium-170 to provide the total energy required and would provide about 16 kW of power, assuming the rover's conversion and distribution system is capable of handling that much power. In both cases, the thermal energy available to warm the rover allows for total heat transfer rates much higher than assumed in the thermal analysis done earlier. Note that radiation shielding required to protect sensitive electronics has not been accounted for.

In terms of mobility, terrain and obstacles are considered "significant" or are important considerations to a rover system when they are of a size similar in magnitude to the rover itself. In other words, whereas a 1 centimeter pebble is significant to a rover wheel only a centimeter in diameter it is insignificant to a one meter diameter rover wheel. It is also true that if a rover is small enough compared to the obstacles and the distribution of the obstacles affords enough clear space between them to allow a small

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rover to pass, a small rover could be considered more mobile that a larger rover in a given terrain. An example of this might be a boulder field of 1-meter sized boulders with 1/2-meter wide clear zones between them. A 1-meter rover must go over the boulders, whereas a 1/3-meter sized rover can fit between the boulders. Determining whether a small rover has greater or lesser mobility than a large rover depends entirely on the terrain, and not enough high resolution data exists on the lunar poles to make that determination at this time. Therefore using mobility as a criterion for evaluating a mission using multiple small rovers versus a large single rover does not appear to be appropriate. Some consideration of terrainability of small versus large rovers in lunar soils should be made, however that study is beyond the scope of this paper. Physical scaling laws seem to indicate that as the overall size dimension (i.e., length) of a vehicle is reduced, the surface area of the vehicle reduces by a square power law and the mass reduces by a cube power law. This seems to imply that it is possible that very small rovers would not be able to even move at all in loose lunar soils when one considers that traction is a function of the normal force, which in turn is a function of the mass of the rover. It is also true that in soft soil, traction is determined more by soil shear strength than by normal force or Coulombic friction, and that the amount of force required to cause motion is typically proportional to mass. Finally it should be noted that lunar soil is generally fluffy and loose at the surface and compacts easily. This is likely to have more of an effect as rover size and mass are reduced. This issue is decidedly complex and deserves further detailed study to determine how well small vehicles will perform in lunar soil at 1/6 g.

In terms of mission objectives, performing the drilling operations and any potential excavation operations would appear to favor a larger and more massive rover as opposed to a smaller lighter rover. In terms of overall coverage of the region of interest, the discussion above shows that a single rover can cover a very large area in a 6 month mission, thereby removing one of the major arguments for using multiple rovers, that is, greater area coverage in a given time frame. Finally, a major argument in favor of multiple rovers is system redundancy. Deploying a single large rover puts all of the mission's "eggs" in a single basket. If the rover were to experience a failure or become damaged during operations, the remainder of the rover mission operations must be abandoned. However, when using a group of small cooperative rovers, the loss of a single rover does not bring the mission to a halt although the data return will be reduced in quantity. The tradeoffs between multiple rovers versus a single rover are complex and an optimum configuration is not at all obvious. It would seem that although arguments for and against a single rover can be made, the two criteria that will drive the decision are mission/task dependencies and system redundancy/robustness.

Therefore it can be stated with some degree of confidence that for a mission requiring core samples and/or excavation sampling of soils, a more massive rover appears to be the more favorable choice. In contrast, for missions requiring sensing only of soils or rocks accessible at the surface, a more massive rover is not required. In any mission where there is a likelihood of rover failure due to operating in adverse terrain, redundancy offers significant advantages toward promoting mission success. This scenario would indicate multiple rovers to be the more favorable choice, although there is nothing to indicate that cooperative, swarm-like groups of small rovers is required. Although this paper has not addressed the availability of launchers or lunar landers, they both will tend to dictate the

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maximum mass and size of any rover(s) sent on a lunar surface mission. Having assessed the rover's basic energy and power requirements, a logical next step in evaluating the rover configuration most favorable for the envisioned lunar polar surface mission would be to evaluate what lunar lander technologies or techniques could be brought to bear on this problem successfully. The sum total of the lander, the rover(s), any communications satellites required will dictate the required launcher. Launcher cost and availability will drive the other side of the equation, such that some optimum total rover mass and size can be arrived at for the most effective launcher configuration, which in turn will allow a final determination of the size and number of rovers that can be launched and subsequently landed on the lunar surface.

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