

A lunar Micro Rover System Overview for Aiding Science and ISRU Missions

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ABSTRACT

Current science missions to the surface of other planetary bodies tend to be very large with upwards of ten instruments on board. This is due to high reliability requirements, and the desire to get the maximum science return per mission. Missions to the lunar surface in the next few years are key in the journey to returning humans to the lunar surface [1]. The introduction of the Commercial lunar Payload Services (CLPS) delivery architecture for science instruments and technology demonstrators has lowered the barrier to entry of getting science to the surface [2]. Many instruments, and In Situ Surface Utilisation (ISRU) experiments have been funded, and are being built with the intention of flying on already awarded CLPS missions. However, there are still limited options for positioning these instruments beyond the reach of the lander. There are many benefits to moving instruments outside of the landing zone, such as being able to analyse areas not affected by the landing system or those of geological interest. Micro rovers (rovers with a mass lower than 10 Kg) can lower the barrier to entry for moving small instruments away from the initial landing location. This study describes how a micro rover architecture that supports current instrument Size, Weight and Power (SWaP) requirements, can enable a valuable science return when compared with larger missions such as the VIPER rover and the Chang'e series of rovers.

1 INTRODUCTION

Many missions planned by national space agencies to visit the lunar surface in the coming 5 years focus on the best methods for transporting humans to the lunar surface, and the valuable science that can be achieved once there. The Artemis program represent the most ambitions of these plans with a goal to land humans on the surface by 2024. Robotics has been identified as playing a key part in the development of systems capable of sustaining human lives on the lunar surface [3]. Technology enable efficient use of astronaut time will also be a key stepping stone for human missions further afield such as Mars and space stations in interstellar space, where autonomy becomes much more important in the life support systems [3]. Robots used to explore planetary surfaces have traditionally been in

the form of rovers and landers of various size [4]. Due to the costly nature of these missions, and the pressure for a guaranteed science return, they have been designed to minimise risk by using redundant and high reliability systems. This further increases mission cost as components and subsystems are expected to be extensively qualified.

As an example, the Mars Science Laboratory, nicknamed the Curiosity rover, one of the most successful interplanetary rovers to date, has 10 main scientific instruments, requires a large team of people to control and cost over \$2.5 billion to build and fly [5]. Curiosity had 4 main science goals, with the instruments and the design of the rover specifically tailored to those goals [5]. The mission has achieved significantly more than its initial goals and has furthered our knowledge of the surface of Mars, but it is not suitable for direct use in another mission. The Perseverance rover was planned to copy Curiosity's design to schedule and cost. However, as the design was not as easily reused as initially planned and Perseverance is estimated to be as costly as its predecessor, with the expected lifetime cost being \$2.9 billion. Equally it has been shown that robotic probes and rovers achieve far less science value for the cost and time when compared to human explorers [6].

On Mars there is a strong argument for further use of large traditional science rovers, as human travel to the surface is not expected to be feasible in the near future. In contrast, the Moon has previously been visited by humans, and there is a wealth of knowledge about the surface structure, and conditions on the surface. Therefore, the needs for semi-autonomous lunar rovers differ greatly from those of other planetary rovers. To meet the goal of landing humans on the Moon by 2024, there is insufficient schedule to design a Curiosity or Chang'e (the CNSA large Moon rover series) class rover to survey landing sites, as they have development cycles on the order of >5 years. Additionally, due to budget constraints it's unlikely that it would be possible to fund such a mission whilst maintaining funding for human lander systems. There exist rovers in the build phase, that are planned to launch before 2024, and these will conduct useful science. For example, the Volatiles Investigating Polar Exploration Rover (VIPER), is aimed to land in 2023 in the lunar South

Pole region [7]. VIPER is planned to look for specific volatiles such as water, which may be a prerequisite to long term human presence on the lunar surface [7]. Rover systems that aid specific parts of human landing requirements, such as looking for water are what is needed. Even after human landings, robotics could enhance science activities and perform roles that cannot be efficiently completed by humans due to safety and cost considerations.

2 BENEFITS OF A MICRO ROVER SYSTEM OVER TRADITIONAL ROVERS

In preparation for human landing, areas of the lunar surface need to be identified that will benefit the most from human led scientific investigation. As human time on the surface is expected to be both expensive and limited, pre-selecting promising sites will maximise science return. Furthermore, a better understanding of the weight bearing capabilities of the surface is required before landing heavy equipment. If space agencies invest their budget in landing large and expensive equipment on the lunar surface, there needs to be assurance that the surface can support that weight without collapse. In the case of human crewed landers, or life support systems, it is of even more importance that the surface is safe for use.

As well as the requirement to investigate the surface and sub-surface to ascertain load bearing strength, there is also a need to probe the surface to gain an understanding of its chemical makeup. This would be required to highlight areas of interest for ISRU. Surveying for signs of ice water or precious metals in the regolith, may be a long and laborious task, taking many months and covering many square kilometres. It would be preferable to conduct some of this work before 2024, to inform landing locations for human permanent habitation. Water deposits for example, will be key in defining the location of lunar habitats; locating them is therefore taking precedence in the goals of planned missions such as VIPER, ProSPECT and lunar Trailblazer [7] [8]. Notwithstanding the expected results from these missions, there is a need for large scale analysis of the surface with in-situ measurements (opposed to satellite data), which cannot be efficiently completed by humans in a safe manner using currently available systems, and would need to be partly completed before human landing.

The above reasoning concludes that large scale measurement of the lunar surface, in the form of sub surface probing, regolith characterization or small drilling procedures will be needed in the near future. To perform this measurement, we propose an architecture consisting of several micro rovers of a standard design, with

a mass under 10 kg, with each rover carrying a single instrument. Multiple rovers could be flown on a single lander, reducing mission costs, and allowing a greater area to be covered. Furthermore, this would allow instruments that have specific requirements, which make them undesirable for larger missions, to be flown. For example, an instrument which requires the rover to remain in place for extended periods of time would not be compatible with one which requires large ground coverage; for a large mission, likely only one of these instruments would be chosen. Individual rovers could further be tailored to the instrument's needs by varying the location to which they travel, their speed of travel, and the direction they face. Further modifications could also be made to aspects such as the wheel diameter, ground clearance and power needs. These missions would be transported by a CLPS lander, or similar international alternative. In comparison, VIPER will fly on an Astrobotic lander, as part of the CLPS program, and is planned to land in 2023, but has the disadvantage of consisting of a single large 400kg rover. Though it will provide a valuable insight into the volatile makeup of the lunar South Pole, due to the small amount ground coverage, many rovers of a similar capability may be needed to find the required reserves of volatiles.

In the same way that the CLPS architecture is allowing unprecedented access to the lunar surface through lowering cost and standardising interfaces, we believe that utilising this architecture by with micro lunar rovers can improve upon a traditional rover mission. Using a rover allows the mission to have a higher spatial coverage and can take an instrument outside of the sphere of influence of the lander, but traditional rovers can usually only do a small portion of an area. Many smaller rovers can cover a much larger area, increasing spatial coverage. Properties of the lunar surface are likely to have been impacted by the lander's engine. A small rover could take a single instrument to a point where the dust has been affected much less, or to find dust that has been moved by the process, depending on the mission parameters. This is an additional understanding of the lunar surface and the way human landing systems effect it that we do not yet have, and will not have conclusively until we probe it with movable instruments. Using a rover such as our micro rover can also allow for a controlled and precise sampling of these affected areas that a human may not be able to achieve in person, as they cannot reasonably sample some forms of regolith without disturbing it. This method of using small rovers allows space left on the lander to achieve other goals, using static instruments or other rovers.

3 EXAMPLE PAYLOADS FOR A MICRO LUNAR ROVER

There is a wide range of potential instruments that would be suitable for use on a lunar micro rover, and benefit from the movement of the instrument from a lander; we have outlined four of the most likely candidates, using instruments with a mature Technology Readiness Level (TRL). We are therefore confident that the SWaP characteristics described can be achieved.

3.1 Ground Penetrating Radar (GPR)

GPR is a common addition to modern planetary science missions as it allows for high quality measurement of sub surface geology, has a low cost, requires a short amount of time to operate and most instruments have the ability to change their precision and range through their software. An example is found on the Perseverance rover with the Radar Imager for Mars' Subsurface Experiment (RIMFAX) instrument, a 3 Kg 199 x 120 x 6.6 mm (<0.5U), 10 W GPR that has a resolution between 15 and 30 cm [9]. Another example, specific to the Moon, is the LPR instrument aboard the Chang'e 4 rover, has been described as having a probing depth of 30m with a 30cm resolution, to 100 m with 10 m resolution [10].

If GPR was used on Earth to survey an area, the person or robot surveying would go up and down an area so that a 3D map can be developed that shows how the area is made up in terms of geological layers. Creating a 3D map improves error correction, and makes it easier to notice and pick out erroneous results. 3D maps also have the benefit of understanding changes to geological layers in two dimensions, and may help in understanding geological processes under the surface. On most large rovers, including the ones mentioned above, the GPR is very much treated as a passive instrument, which takes a measurement every few centimetres along a journey. The GPR very rarely defines the overall journey itself, with the driving often being a straight line, or easy to navigate route between two interesting areas that need to be inspected. Equally the versions that humans use to measure areas on Earth are often bulkier than mentioned, with large handles and systems to make the GPR go the correct direction with ease when being handled, including marking out areas beforehand, a monotonous job that a robot would be very good at. If a GPR were to be the only instrument on board a small rover the science requirements that define operations and routes would vary vastly from traditional rover driving, and therefore a micro rover would allow for science not seen before on the lunar surface.

There are a number of small GPR instruments being developed by different groups, with the miniGPR by JPL being of a realistic TRL for near term missions. The miniGPR has a mass of 1.5 kg, size of 2U and consuming peak power of 1W when operating [11] [12].

3.2 Neutron Spectrometer

Neutron spectrometers have been shown to be a very useful route to finding water and other volatiles on the lunar surface. The lunar Prospector mission employed a Neutron Spectrometer to achieve this exact goal, and this has led to the strong discussion around ice and the lunar Polar Regions, that has spurred on missions like VIPER [7], lunarICE [13], lunar Trailblazer [14] and LUVMI-X [15]. The key to the future of using this type of instrument on the Moon is to get ground truth, but placing neutron spectrometers nearer to the surface, with longer timescales allows for much more reliable data and a better chance of finding exact locations.

As with the GPR, neutron spectrometers can be seen as a passive instrument, and if it were to be designed into a package, such as on the Neutron detector (ND) as part of the Radiation detector (RD) instrument aboard the LUVMI-X rover, it would be an additional verification of where to use drills to actually prospect for potential water sources [15]. Using a micro rover would allow this initial searching step to be separated from the expensive and heavy main rover with the complex mechanisms to drill into the surface and analyse samples. A small rover, or multiple small rovers could look at an entire area and pick out areas most likely to have the deposits desired, minimizing drilling, and the likelihood of breaking key drilling equipment which cannot be replaced easily in flight.

There are many instruments that can have a neutron spectrometer as part of a package of instruments, but if required on its own, the miniNS developed by ASU is a realistic benchmark for a designed device. The device measures protons (and by implication ice) abundance to a depth of at least 1 meter, with a weight of 0.5 kg, a size of 1U, and a peak power of 5 W when operating [12].

3.3 LIBS Spectrometer

LIBS Spectrometers have been found to be useful and often powerful tool in the analysis of specific minerals on the surfaces of other planets. The ChemCam instrument for instance has been one of the most useful systems in the suite of instruments on the Curiosity rover, and has yielded huge benefits in terms of science. Alt-

though ChemCam is a large and hugely powerful instrument with large amounts of redundancy, LIBS spectrometers are known to be easily modifiable depending on the application, and could be made smaller than 1U if aspects such as a movable head and redundant spectrometers are removed [16].

In practice on large rovers, LIBS spectrometers have been used as the first shot at a particular rock or area of interest, and gives a good indication of the chemical composition of a certain material. Larger rovers would then probe the area for ground truth, and drill holes and take better readings with more elaborate instruments. In the case of the Moon, apart from the use as a measure of rocks and geological interests, a LIBS spectrometer is particularly useful to find volatiles, such as water. The Volatiles Identification by Laser Analysis (VOILA) Instrument aimed to be used on LUVMI-X is an example of such an instrument that can use this probing method that is optimized to detect hydrogen and oxygen. This allows the detection of certain areas most likely to find high volatile content [16]. If a LIBS spectrometer slightly smaller than VOILA was used on a micro rover, it could allow for scouting rovers to look for those hotspots, that larger rovers could then come along to probe more efficiently. The VOILA instrument is 1U + an optical head, with an overall mass of 3 Kg and a peak power of 10W when operating [16].

3.4 Magnetometer

Understanding the magnetic field around planets and stars has been a key part in our understanding of how they work, how the inner sections move and interact, and how they have developed over time. On the ground magnetometers can provide localised information about the magnetic field, and provide key information for science in terms of the structure below the surface, something that could be key to both the science community and the ISRU community.

Magnetometers have a rich history in spacecraft, and can be changed depending on the requirements of the specific mission in question. Much like the previous instruments, magnetometers can be seen as fairly passive, as they will measure the field wherever they may be. The areas required to measure magnetic fields could be quite large, and may require consistent and prolonged readings that could be wasting the time of other instruments on board the rover. Therefore on a micro rover, those requirements could be more defining for the mission operations. Rovers could also be used as stations to move to a set location, a certain distance from a lander, and then stay there to become a monitoring station. This is only beneficial when all the instruments on board benefit from the sustained stay.

The magnetic field of the Moon is still a very much open area of study, and small instruments are being developed for the purpose. Compact Flux Gate Magnetometers (FGM) are readily available, for example one was flown on ELFIN, a 3U CubeSat [17], and Vectorised Magnetometers (VHM) are under development, but could be hugely beneficial in the near future due to superior stability, with the increased need for resources. In tandem a dual magnetometer could be hugely powerful if used correctly. Such an instrument using current estimates would be 2 kg + booms, and 1-3.5 W peak power (depending which instrument is being used) with a volume of 2-2.5U needed plus booms [11].

3.5 Other Potential Instruments

There are a huge amount of potential instruments that could be developed or utilised better by a micro lunar rover mission, and would have benefits from being the single instrument on board. Also plenty of these instruments can be modified to reach the SWaP requirements of such a rover.

miniENA an electrostatic analyser, and miniESA an energetic neutral analyser are both suitable for the lunar surface, and could be beneficial for missions, with both being less than 1 kg each, each drawing 1 W, and taking up 1U of space. There are also many micro imaging systems that are below 2U, weighing 1kg and drawing 5 W, all having specific scientific aims and abilities. Examples would be the MMI micro imager, and the RAL CubeSat camera [11].

4 DESIGN DRIVERS FOR A LUNAR MICRO ROVER

This paper describes the reasoning for the use of a micro rover in the lunar environment, and the types of instrument that would be suited to such a technology. As part of this study, a number of design drivers have been established, and they describe the basis of an architecture for a standardized mission for the micro rovers in question. This can then form the basis of future concepts such as specific mission aims, and technical requirements around those aims.

This paper does not aim to outline design or requirements for a rover landing architecture system, but instead uses the payload user guides for the Peregrine lander by Astrobotic used as the first CLPS mission in July 2021, and the XL-1 lander by Masten Space Systems used as the third CLPS mission in December 2022 as the basis for a landing system. AS a note, the Masten mission will employ the MoonRanger developed by Astrobotic as one of the payloads for NASA, but it is not yet clear on the delivery mechanism, and

it is likely to be around 13kg without payload. Although the above user guides do not include information specific to rovers, it describes the concept of delivery, and the services available and required for a successful mission.

4.1 Model Instrument Baseline

For use as a baseline design driver, using the instruments outlined in section 4, there are a number of SWaP values that apply to almost all of the instruments. As a basis, it is safe to assume that a reasonable instrument for a micro rover:

- Takes up 2U of space (100 x 100 x 200mm).
- Has a mass of 2 kg, evenly distributed.
- Draws a peak power of 10W.
- Draws 1W in general use.

This baseline instrument can be used to develop a detailed design, and will allow for more understanding of requirements for such missions.

4.2 Design Drivers for a lunar Micro Rover

Based on a study underway within RAL space, where the information from this paper has been derived from, a number of key drivers have been understood to be needed as part of future design work.

- **The electronic bus** of the rover needs to be standardized and based as much as possible on off the shelf solutions to allow the design to be cheap enough to be competitive. A potential route is to utilise CubeSat components with reliable testing and/or heritage.
- **Pre-flight testing** is an area that should be standardized, and understood as part of the community. Similar understanding already exists within the science satellite and CubeSat communities, and well known processes can be followed. It needs to be understood to what level a rover needs to be tested before a mission to ensure reasonable success.
- **Thermal materials** are a known problem within the lunar community, and a small rover with limited power supply available could be susceptible to major swings in temperature, which could be disastrous for a science instrument on board.
- **Reliable semi-autonomy** is a key area of research that needs to be developed to enable cheap and easy use of these small rovers. There are reliable algorithms that can be utilised, but understanding applications within

the strict safety requirements of lunar missions can be a difficult problem.

5 SERVICES REQUIRED

The system envisioned requires a set of key infrastructure that currently does not fully exist, but is likely to be set up as part of lunar activities in the coming 5 years as part of the human activities planned. Some sections also are very likely to be fully shown to be possible in the next year, such as the CLPS landers.

5.1 Travel to the Surface

A key driver that was once the largest barrier to entry for access to the lunar surface is the ability to get small payloads to the lunar surface. Due to the CLPS program, and an increase in mostly American companies designing capable lunar landers, there is now a competitive end-to-end service. It also has the benefit that there are now many slots available on missions partly funded by NASA. It is expected that there will be up to 2 missions a year, with some differing capability as to the lander itself. As part of this study we used the user guides for Masten Aerospace and Astrobotic, which have both been assigned CLPS missions.

Baseline figures for a trip to the surface of the Moon is that it takes 3-5 days, with most missions landing lunar morning, and functioning reliably until the lunar night. For some early missions this time can be as low as 192 hours, some can be as long as 13.5 days. The current baseline is that all activities and communications need to be achieved in this time. Other considerations such as vibration, mechanical, EMC and outgassing can be found in the relevant user guides and must obviously be followed.

5.2 Communications Architecture

There is no current reliable data relay from the Moon to the Earth, and therefore missions up to this point have taken a high gain antenna as part of the mission. Some missions have utilised orbiters, such as the LRO data link, but this is not guaranteed. ESA and NASA plan to develop a lunar internet that enabled different spacecraft to communicate with each other effectively, but it is still in the early phases. For this architecture, the communication with Earth is via a transceiver at the lander. The rover to lander connection will be a 2.4 GHz connection to fit in like with future communications plans. This may be via a ZigBee transceiver which is the likely candidate for the MoonRanger rover, or another medium range mesh network transceiver.

5.3 Reliable Surface Mapping

Part of micro rovers having the ability to function in an area requires a quality map of the surface, and a rough understanding of inclines in the surface and the likely material that will be traversed. NASA data from LRO has enabled most of the Moon to be mapped at very fine detail. This allows for realistic mission planning before the mission flies, and a basis for semi-autonomous algorithms to work from as part of their internal processes within the rover.

The science that needs to be achieved also relies heavily on satellite data to define the landing sites, and understanding the most likely places that a certain element or environmental process can be found. This data will also be key in understanding the mission parameters and where the micro rovers will be sent to achieve the specific goals.

5 CONCLUSION

This paper has described the benefits of how micro rovers used on the lunar surface can often be a more efficient and beneficial method of transporting instruments to areas beyond the reach of the lander, when taken from the instruments point of view, and compared to larger more traditional style rovers. Lunar micro rovers could be the next stage in the development of wheeled robots that can work in tandem with human astronauts, and allow the freeing up of valuable time for these astronauts. Laborious tasks such as large area monitoring and characterization can be carried out by a small fleet of rovers that could add up to a similar weight and size of a traditional rover. These individual rovers can utilise the benefit of moulding the mission parameters to the needs to the particular instrument on board. This allows for a much higher quality of science data, and better value for money for the instrument. Once initial designs are standardized and the design drivers laid out in this paper are better understood and solved, the price of such a rover can be drastically reduced, and become an off the shelf product from commercial providers, similar to that of CubeSats. There are many benefits that stem from a design like this, and they will be further explored in future bodies of work to be undertaken by RAL Space and the consortiums created to further access for science on the lunar surface.

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