A roadmap for the robotic facilitation of off-world living

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ABSTRACT

A future human presence on the Moon or Mars will depend upon both robotic preparation and robotic facilitation. NASA, China, Russia (then Soviet Union) and, soon, ESA have operated remote vehicles on one or other of these bodies. While semi-autonomous rovers are an established technology, their capability remains extremely limited when considering the nature of the tasks, (including mining capabilities), that will be required in association with a semi-permanent human presence.

The surface of the Moon or of Mars will, for the foreseeable future, be a very hostile environment: vacuum or near vacuum pressures; large temperature differences; high radiation levels; high dust levels; and unknown unknowns. For this reason, it is likely that humans will wish to minimize exposure to the external environment, preferring rather to live within the relative safety of purpose built structures, possibly beneath the surface.

Building structures 'by hand' is likely to pose too high a risk and so humans will call upon robots to prepare the site, fabricate, manipulate, assemble, integrate and test. This is likely to be more than merely 3-D printing of structures but would also include maintenance, repair and the flexibility to deal with unexpected developments. During the preparatory phase, it may be that just a minimal human presence on the Moon is needed and the remote control of robots from the Earth may be more effective, less risky, and a great deal less stressful.

Here we take a systems approach, exploring first a set of high level capability requirements and then considering a ConOps (Concept of Operations) trade for those necessary activities that could be performed off-Moon. This is within the context of the planned return to the Moon using the Gateway platform and through international cooperation. Such considerations will be needed to inform a coherent and extendable roadmap for the exploration of the Moon and Mars.

KEYWORDS: Robotics, Lunar Exploration, Systems, EVA

INTRODUCTION

During the Apollo era, it was natural to assume that an ongoing human exploration of the Moon would ultimately lead to a permanent human presence – a community on the Moon. Only now, 50 years after Apollo, are we preparing to re-visit the Moon, (see e.g. [1, 2] for the reasons for this). Numerous texts and studies have been published regarding almost every aspect of such an endeavour, (see e.g. [3,4,5](Power), [6](Navigation), [7](Lunar Construction), [8](Lunar propellant manufacture), [9](Regolith Robotics), [10](Habitation), [11](Communications). The Global Exploration Roadmap Critical Technology Needs which includes lunar exploration can be found in[12]. Recently we have seen a sustained and committed programme with multiple actors, governmental and private, a very significant growth in lunar missions and widening international participation.

Following the dominance by the USA and the USSR of lunar exploration in the 1960's and 70's, we have more recently seen lunar missions from the major space nations China, India. Indeed, the emerging space nations are also showing an interest in the Moon with missions from Luxemburg and Israel, and missions planned from Mexico, South Korea and Taiwan. Moreover, 48 years of near-Earth human spaceflight experience through space stations (Salyut 1-7, Skylab, Mir, and International Space Station) have allowed humanity to better understand the challenges of prolonged space flight and to mature the technologies of resupply and docking.

ARGUMENTS FOR A RETURN TO THE MOON

Many arguments have been made for a human presence on the Moon; see e.g. the Global Exploration Roadmap[13] .

From a scientific point of view, the Moon itself is of great interest. It can tell us much about the early solar system and the formation of the planets. As a very different body from the Earth, it permits the formulation and testing of more general geological models that can be used elsewhere in the solar system.

The Moon provides an unparalleled vantage point for astronomical observation, especially on its far side. The great observatories in space are reaching the limits of their practical dimension and associated cost. While the James Webb Space Telescope will no doubt provide data of incomparable quality and exactness, the generations of space telescopes to follow become increasingly difficult to imagine. The JWST, while exceptional, has a cost of nearly $10B[14]. Radio astronomy from the far side of the Moon offers a very low noise (free from human interference) location and also the possibility to study the universe at wavelengths greater than 30 m[15,16,17].

As a 1/6th gravity environment with access to very high vacuum, the Moon provides a unique laboratory and manufacturing environment – who knows what this may yield.

Some argue that the Moon is a lifeboat in case the world becomes either too polluted or is made uninhabitable through the impact of a large body. Creating a sustainable lunar community might be a way to ensure the survival of humanity. Perhaps a stronger argument could be made for Mars in which case, given its relatively convenient proximity to the Earth, the Moon is surely the best place to develop the technologies (and much else) necessary to create a Martian settlement. Certainly, the Global Exploration Strategy sees the Moon as a gateway to Mars, asteroids and beyond[13].

In the context of Space Resource Utilization (SRU), currently there are probably no resources needed on Earth that would warrant the costs of extraction from the Moon[18] with the possible exception of ^3He should fusion power generation become a reality[19,20]. It has been estimated that to provide 10 % of our energy needs, an area of 500 km^2 of lunar regolith would have to be mined for ^3He every year and that the Moon contains enough ^3He to fulfil all our energy needs for 200 years[18].

Given the huge gravitational potential well of the Earth, resources for cis-lunar space and solar system exploration might very well be more cost-effectively provided from the Moon. Key resources include hydrogen, water and oxygen (for life support and rocket fuel), iron, aluminium, titanium, rare earth elements and even silicon (for solar panels)[18,21,22].

Since the amount of sunlight falling on the Moon at any one moment is ~1000 times the world's energy supply, beaming energy from vast lunar solar farms could significantly reduce our terrestrial power generation needs (e.g.[23,24]) and our CO_2 production. Placing solar panels across the 500 km^2 area mentioned above in the context of ^3He extraction would yield almost as much power year after year. While it is appropriate to consider the ethics of processing large areas of the lunar surface, this has to be balanced with the benefits to the Earth's ecosystem of securing energy resources from the Moon (see e.g. [25,26]).

The Moon also can be seen as a commercial opportunity through tourism (e.g.[27,28,29]).

Apollo has had very profound impact on many aspects of society, above and beyond lunar science and exploration, (see e.g.[30]). In that spirit, creating a presence on the Moon can be seen as a vehicle for innovation[31], and an opportunity to improve international relations.

Just as Apollo was an opportunity to demonstrate a nation's technological excellence and a super-power's credentials, a return to the Moon would serve a similar purpose. Super-powers will see leadership of a major lunar programme as evidence of their status in the world while other nations can show their contribution to such programmes as demonstration of their technological prowess.

Finally, many argue that mankind **must** populate the Moon, it's part of our nature.

The above arguments appear to have become compelling and the question today is not "Why are we going back to the Moon?", but when, how, to do what, and for how long?

TARGET CAPABILITY

In order to bound this discussion and based on the reasons for lunar exploration given above, the following near-term capabilities for a human presence on the Moon are set as goals:

0. (To be able to arrive on and leave the Moon)
1. To be able to landscape the local lunar environment
2. To be able to create structures such as habitations and handle bulky items (such as mining equipment)
3. To access geological resources such as water or minerals
4. To be able to accommodate and sustain a group of humans indefinitely, albeit with external supplies
5. To be able to conduct geological, scientific and astronomical observations
6. To be able to move from one location to another
7. To suffer no significantly greater risk from natural or man-made disaster than on the Earth

The 0th capability (in brackets) is not part of this discussion. It will be assumed that the necessary infrastructure for Earth-Moon transfer, e.g. via a Gateway platform[32] will be in place. The preparation of landing and launch sites is covered by the 1st and 2nd capabilities

The Moon presents some significant difficulties to be overcome. These include:

- The hostile lunar environment, (vacuum, radiation, thermal, dust, low gravity)
- The logistic associated with Earth-Moon transfers
- Lunar geology including the nature of the regolith

To guide the discussion, we adopt two general principles:

Koelle's 2nd law states that 'What your can do on Earth, you should plan to do on Earth and not in space!" and is often cited in the context of human lunar exploration[10,33,34]. However, practically there has to be a trade between Moon-based and Earth-based implementations. To avoid being overly restrictive yet still keeping the spirit of Koelle's law we adopt the following principles:

- First principle: Wherever possible trade the option to do it on the Earth rather than the Moon.

The associated trade study should take into consideration practicalities, risks, cost and schedule.

The second principle comes from the nature of the environment. While images of lunar settlements invariably show individuals in space suits moving between structures, in practice this behaviour should be avoided if possible. It is inherently dangerous and hugely inconvenient[35]. Rather, allow robotics to take the strain either through remote control or through automation and artificial intelligence. Therefore, we adopt:

- Second principle: Wherever possible avoid EVA's.

While it is acceptable for Apollo or low Earth orbit astronauts to spend considerable time in preparing and recovering from EVA activities, and to endure the rigors of uncomfortable and cumbersome spacesuits, this can hardly be a model of normal lunar activities. Apollo space suits and backpacks had a mass of 88 kg, ISS equivalents are 285 kg. While the new NASA suit (Exploration Extravehicular Mobility Unit, xEMU) is indeed highly sophisticated and has evolved significantly from the days of Apollo, it necessarily appears bulky (although the mass including portable life support system is thought to weight around 73 kg) and not something that would be donned casually[32]. While NASA's approach is inevitably an evolution of Apollo, the concern must be that to evolve further towards a semi-permanent presence it must involve either a revolution in EVA spacesuits or the general elimination of EVA activities as part of a normal working pattern.

The radiation and thermal environment suggest that humans on the Moon will spend most of their time below the lunar surface, either in structures covered by lunar regolith, or in natural sub-lunar pits or lava tubes[36,37]. Where practical activities on the surface will be remotely controlled, possibly even from as far away as the Earth (through the application of the first principle).

To create the capabilities described above it is not necessary to create a township but rather something more akin to the Antarctic bases. The evolution to a lunar settlement is therefore beyond the scope of this work. However, it is nevertheless noted that any approach to meet the above capabilities should be extendable to the creation of a settlement on the Moon and on Mars.

INTERNATIONAL COOPERATION

We take the possibly ideological view that any general semi-permanent human presence on the Moon is likely to be international in its making. To justify this we make the following arguments:

- The 1967 Outer Space Treaty (available at[38]) is essentially international in its treatment of space.
- The Global Exploration Strategy[17] is intrinsically international.
- The current Artemis programme[32], although very much US led, is an international endeavour that includes Japan, Canada, the ESA nations and Australia.
- The costs and investments are probably too great for a single nation to bear while the advantages of pooling expertise and resources are compelling[39].

It is recognized that while returning to the Moon in 2024 is a significant step forward, it is only the very start and a modest outlay compared to the costs associated with a more permanent settlement. Private investment must play a vital role, (e.g.[40]) separating the endeavour from the impact of changing political priorities (see e.g.[33,41]. The ARTEMIS protagonists have to make sure that this new mission does not become merely Apollo 18. Nevertheless, there remains 'no clear scenario for achieving economic feasibility of lunar development' and there is 'no business case for investments in [the] Moon that are not dependent on government funding'[41].

It was hoped that the UN 'Moon Treaty'[42] (more correctly: 'The Agreement Governing the Activities of states on the Moon and Other Celestial Bodies') would provide the necessary framework for lunar exploration and settlement; however with only 18 signatories, not including China, Russia, Japan, UK or USA, and much skepticism, there is a danger that nations will go their own way. This has begun with US[43] and Luxemburg[44] legislations.

ELEMENTS AND STRUCTURE

In table 1, we decompose the capabilities into a set of functional elements. At this time we will not say what these are or where they are located.

Capability	Functional element
C.1. To be able to landscape the local lunar environment e.g. site preparation	• Access to power source or power generation* • Surveying* • Equipment control • Reshaping the regolith including leveling, slope manipulation, digging, back-filling and covering of structures* • Moving or destroying large rocks*
C.2. To be able to create structures such as habitations and handle bulky items (such as mining equipment) e.g. creating the infrastructure prior to its use	• Access to power source or power generation* • Transport of bulky items* • Loading and unloading of bulky items* • Storage of bulky items* • Preparation for assembly* • Assembly of structures including mechanical and electrical integration*
C.3. To access geological resources such as water or minerals	• Access to power source or power generation* • Surveying (local* and global) • Equipment Control • Mining* • Drilling* • Digging* • Loading, unloading and transportation of material* • Storage of material * • Processing of material* • Storage of processed materials* • Distribution of processed materials*
C.4. To be able to accommodate and sustain a group of humans indefinitely, albeit with external supplies	• Access to power source or power generation* • Life support* • Food creation, storage, preparation* • 'Hotel functions'* • Communications (local, including cis-lunar, and to Earth)* • Enabling social interaction and leisure • Management functions
C.5. To be able to conduct geological, scientific and astronomical observations	• Access to power source or power generation* • Transportation* • Sample collection* • Sample analysis • Remote operations • Local operations* • Extended EVA* • Data acquisition* • Data transmission* • Status reporting* • Data processing • Maintenance (including cleaning)*
C.6. To be able to move from one	• Access to power source or power generation* • Transportation

location to another	• Navigation (local* and global) • Transport equipment maintenance* • Shirt-sleeve connectivity between functional areas*
C.7. To suffer no significantly greater risk from natural or man-made disaster than on the Earth	• Appropriate safety standards • Safety cases • Hazard awareness, monitoring • Contingency measures

In the above list those marked with a * are necessarily provided on the Moon.

The items not necessarily present on the Moon are discussed below:

Equipment Control

C.1.landscaping, C.2.building and assembly, C.3.resource related, C.5.science

Since the days of Lunokhod[45] equipment has been operated on the Moon. The 2½ s return light travel time does permit near real-time control. Indeed, rovers operate on Mars, albeit extremely slowly, with enormously greater latency. Therefore, there is no *a priori* reason to require that all equipment be operated locally.

Applying the two principles mentioned above could lead to one of the following concepts of operation:

a) Equipment is installed by astronauts but operated remotely from Earth to prepare for later, semi-permanent human presence. The first wave of astronauts creates an outpost from which site preparation and assembly functions can take place but then retreat to the safety of the Earth while such preparations are performed. Perhaps returning intermittently for maintenance and other specialist functions.

b) Equipment is installed by astronauts but operated remotely from within lunar habitation. While this has the advantage of local actors, it could violate the first principle since remote operation could be more cost-effective than maintaining a local astronaut community for a prolonged period in a relative uncomfortable situation. The rapidly developing AI technology is likely to play an important role here if only to prevent mishap during the 2½ s latency. However, a fully robotic site and habitat preparation phase is not suggested, partly because it would appear unlikely that the necessary technology would be available and partly because that is not the way that NASA sees its return to the Moon[32].

The role of a crewed Gateway in Lunar Orbit is considered. The Gateway would have visibility of the far side of the Moon and so provide a communications link to any facility that is not in direct contact with Earth. However, this need not be crewed. A lunar surface habitation will be safer and more comfortable than an orbital space platform, weightless deterioration of the human body will most likely be less, although very little is known about the prolonged effect of 1/6 g. The role of the 'Command Module Pilot' may be obsolete.

While Humans are mostly likely to be required to install, commission and maintain equipment for the majority of the objectives stated above, continuous human presence is not required. It may be that an 'as-needed' short-term presence together with extensive use of AI and Earth-operated robotics could well satisfy our short-term needs. Space tourism, if delivered on a continuous basis, would be the exception although in practice the 'Hotel staff' might well travel to and from the Moon with the guests.

Sample analysis and data processing

C.5. sample analysis; data processing

With human presence on the Moon it is very likely that the quick-look analysis of lunar samples could best be performed locally rather than shipping them back to the Earth. For science research and to satisfy the needs of the science community, significant amounts of material would be returned to Earth for more detailed investigation. Exactly where the line between 'quick-look' and 'detailed' lies will depend upon a trade study which is likely to change as the human presence on the Moon grows. Note however that to avoid sample contamination caused by the passage of material back to Earth, local studies may be preferred.

The site of any very extensive data processing is subject to available communications bandwidth. If this bandwidth is sufficiently large the data processing of e.g. radio astronomy data, might best be performed on Earth.

Enabling social activity and leisure

C.4. Enabling social activity and leisure

For a small semi-permanent human presence an ISS approach to social interaction and leisure activities may be appropriate especially if the background of the individuals is similar to that of the ISS astronauts (i.e. military service personnel, trained specialist, psychologically screened). However, it is known that being on the Moon and observing the Earth from that vantage point (on the near side of the Moon the Earth will be visible in the same part of the sky all of the time) has had psychological effects on some of the Apollo astronauts (see e.g. the 'Overview Effect'[46]. Careful consideration will need to be given to this issue as the human presence on the Moon grows.

Legislation including safety

C.7. safety

In the future, a self-governing community might be established on the Moon but until then it is likely to come under the auspices of an Earth-based authority. Legally there may be some very complex issues here, especially when the public (i.e. through Space Tourism) or Private Industry become involved.

It should be noted that the natural evolution of Apollo with Artemis is much like an extension of a US-NASA administration and, no doubt, ISS arrangements will be the baseline. For a truly international endeavour, genuinely international governance will be necessary.

STANDARDS

In the above, we can envisage a largely robotic assembly and operation of a lunar settlement by internationally diverse players. An essential perquisite for this will be the agreement of interface standards both mechanical (flanges, doors, seals, lifting fixtures, assembly fixtures,), power and communications (across the entire range of the Open Systems Interconnection (OSI) layered model[47].

The existing International Deep Space Interoperability Standards[48], involving the partnership of the five agencies operating the ISS (NASA, Roscosmos, JAXA, ESA, and CSA) should be a relevant basis to develop adapted standards for operations around and on the Moon. It should be reminded that the necessity of adopting common standards, started among the two space super-powers almost 50 years ago to prepare for the Apollo-Soyuz rendez-vous in 1975, then became compulsory among the ISS partners in the 90's.

CONCLUSION

There appears to be sufficient and compelling argument for a future human presence on the Moon. However, this should not be seen as a simple extrapolation of the Apollo programme. Some profound realizations are required to guide this international endeavour and to create a coherent and extendable roadmap for the exploration of the Moon and Mars.

This grand international undertaking will require international cooperation, solutions and governance. Standards will need to be established across many fields and at many levels. While the ISS has made a start in this area, the breadth of international standards for international lunar operations is much more extensive.

The difficulties and dangers of lunar EVAs must not be underestimated. Also, advances (and anticipated future advances) in robotics and artificial intelligence should be taken into consideration. While human presence may be necessary for the installation and maintenance of lunar hardware, it is not at all clear that day-to-day operations need be controlled from the Moon itself.

We suggest above two principles that can be used to support decision-making in this area. The first requires that all activities proposed to be undertaken on the Moon should be subject to an Earth vs Moon trade study. The second seeks to reduce lunar EVA to a minimum.

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