Towards a Lunar Exploration Technology Adaptive Roadmap: Contributions from SGAC's Technical Unit Research for a Thriving Lunar Ecosystem

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Abstract

In the expansion of humanity's presence beyond Earth, the Moon will play a key role both as a stepping stone and as an outpost for deep space operations. For this to occur, it is imperative to begin working towards the integrated development of interoperable technological capabilities that can ensure the thriving development of the Moon.

To shed light on these topics, in September 2020, the SGAC Space Exploration Project Group established the Technical Unit Research for a Thriving Lunar Ecosystem (T.U.R.T.L.E.) with the goal to coordinate original and innovative lunar research from the young generations. The T.U.R.T.L.E. Group focuses on five foundational areas: landing sites, logistic coordination, power supplies, biospheres development and dust mitigation. By examining these domains with a holistic approach encompassing their interactions and implications for multi-year, multi-actor scenarios, the research conducted by the Group aims to be instrumental for the global development of a Lunar Exploration Technology Adaptive Roadmap (L.E.T.A.R.). Ultimately, the main goal of the Group is to support the establishment of a circular Lunar ecosystem, an environment where both competition and cooperation can thrive while sustainability is ensured.

This paper provides an overview of the project structure and presents the main results achieved by the Group after its first year of research. Based on these findings, the paper demonstrates the usefulness of holistic and concurrent approaches to lunar technology development as enabling instruments to be leveraged by young generations.

Please note that this abstract is submitted under the auspices of SGAC, as part of the activities of its Space Exploration Project Group.

1. Introduction

An increasing number of actors are planning new missions to the Moon. As the closest destination in the Solar System and as a celestial body with abundant resources, the Moon is at one time a strategic outpost for exploration, a training ground for technological development, a destination of scientific interest, a driver for economic growth, and a shaping factor in international relationships. This implies that not only the number of projected missions is likely going to increase, but that the scale of such missions will grow too. Establishing human bases, research facilities, mining sites, processing plants and spaceports will require the deployment of heavy and advanced assets. In turn, this will necessitate specialized infrastructure and dedicated services for sustained operations.

The escalation of these activities and of the consequential occupation and utilization of the Moon's surface might at some point have to deal with the inherent scarcity of the most strategic and sought-after sites. This can cause the rapid build-up of political tensions and operational risks, and stifle the overall development and growth potential that could be unlocked through a more carefully planned use of space and resources. Technology can play a critical role in this picture and act on multiple levels. Interoperable technologies and standardized interfaces and protocols can enable shared utilization and decrease the need for surface occupation and overly redundant deployment of assets, while also simplifying maintainability and repairability. Integrated and concurrent technological development of spaceports, power systems and habitats among multiple stakeholders can inform the parallel design of the supporting infrastructure and significantly optimize the subsequent logistics. Moreover, an international and multi-stakeholder development would promote cross-fertilization and spur additional innovations and improvements.

Following these principles, the Space Generation Advisory Council's (SGAC) Space Exploration Project Group (SEPG) established the Technical Research Unit for a Thriving Lunar Ecosystem (TURTLE) with the goal to carry out research on key topics of lunar technological development in a holistic, multidisciplinary, horizontal framework.

A similar approach can help unveil critical gaps and opportunities in lunar technical research and help identify areas where international cooperation and collective efforts might yield the greatest benefits. The Unit is currently constituted by five research sub-units, each specialized in a specific domain, namely:

- Landing sites and spaceports
- Logistics and infrastructures
- Biospheres
- Power
- Dust mitigation

This layout and breakdown of research areas is not static and is meant to adapt and expand to fit the evolving landscape of technological progress and stakeholders' plans and needs. The findings from each unit will converge into a Lunar Exploration Technology Adaptive Roadmap (L.E.T.A.R.). LETAR is conceived to be a flexible and decentralized framework for collaborative and iterative technology development planning, open to contributions from a variety of stakeholders and subject to collective validation mechanisms and peer-review.

The baseline configuration of LETAR will be illustrated later in the present work, after an overview of each TURTLE sub-unit's scope, objectives and findings.

2. TURTLE Research Areas and Key Findings

2.1 Landing sites and spaceports

When considering landing operations in the context of a renewed and growing interest towards the Moon, it is of paramount importance to prevent a "far west" scenario by acting early, before traffic increases, to foster coordination and cooperation in the creation of a set of recommendations for the decades to come. The risk of initiating and perpetrating activities that are not sustainable in the long term should be reduced as much as possible. A pessimistic future, one where agreement was not met between the different actors, is likely to increase the risk for incidents and collisions. Not to mention that these events might affect diplomatic relationships between the involved entities and trigger or sharpen frictions between them. In addition to that, several years of intense human activities without regulation are likely to change the lunar surface and orbital ecosystem. Finally, the accumulation of debris and depleted stages on the surface and in the Moon orbit will be inevitable, especially if no kind of waste management or repurposing cycle is put in place. The failure to determine a plan to access and exploit the Moon and its resources in a sustainable way is likely to jeopardise its exploration for future generations.

Preventing these scenarios, instead of searching for a remedy afterwards, motivated the TURTLE group to focus on several points. The team researched future targets and points of interest on the surface of the Moon, selecting main areas where to focus for regulation. Then, activities were directed to the design of future landing sites, searching for landing site selection criteria and for the best combinations of services to be provided in the direction of a sustainable lunar spaceport. Finally, the considered potential scenarios of future traffic towards the lunar surface require a regulation plan that shall lead to the establishment of regulatory authorities and infrastructures, for which the group presents some considerations and aspects that are critical for a peaceful, safe and sustainable exploration and exploitation of the Moon.

2.2 Logistics and infrastructures

With 95 lunar missions planned by 2030, a variety of state and private actors are planning activities that may develop in close proximity to one another. Actors may find themselves in competition over similar regions, activities, and resources. For a number of reasons, it is not yet clear whether, or to what degree, states will pursue cooperative, independent, or perhaps even competitive exploration strategies. This is a complex issue that intersects technology, mission operations, and policy, with significant implications for international lunar development. Cooperation may reduce duplication of effort and increase international ties between actors. Competition, if well-managed, may catalyze nation-state attention and investment. If poorly coordinated, however, competitive strategies may result in the unnecessary duplication of effort, higher costs, and increased international tensions.

Modeling how infrastructure and logistics might impact leading space nations' decision to cooperate or compete for resources and opportunities on the lunar surface generates answers to three important research questions:

- Can we anticipate the pursuit of cooperative or competitive strategies?
- What role might infrastructure and logistics play in the choice of strategy?
- Can working groups like SGAC leverage these findings to guide state behavior in a more productive direction?

The research approach is threefold. First, key locations and activities are identified. These include the lunar surface locations where actors might operate; the significant infrastructural pursuits that form the core of state lunar development campaigns, like habitats, mines, or landing pads; and logistics that enable the operation of such infrastructure, including the transportation of power, propellant, utilities, and cargo. Second, rational actor behavior is simulated in a resource-constrained, two-player lunar environment using a framework of game theory and decision science. The two counterparties choose to negotiate the exchange of resources and capabilities or operate independently, with both pursuing their own lunar exploration goals in close proximity to each other. Third, the outcomes of player strategies over a number of sessions are evaluated, as well as the effect of those strategy choices on the overall success of lunar development. Interviews were conducted in the early stages to improve the fidelity of our model and approach.

What is novel about this approach is that the experiment is built within the structure of a game. At IAC, the team is conducting a highly interactive special session workshop where teams of IAC attendees act as the space agencies of leading spacefaring nations. In a tabletop board game format, they will deploy assets and negotiate to maximize their exploration "score", meaning the establishment of a full lunar base, and the accomplishment of secondary exploration objectives. Whether they choose to compete or cooperate is up to them, and the team will evaluate the strategies they pursue in order to maximize their payoff.

This IAC session is effectively a beta version of a more comprehensive tabletop strategy simulation workshop planned tentatively for 2022. Using feedback from the IAC session participants, and the results of play, the team will refine the mechanics of the model, and turn it into a serious, multi-day, tabletop "wargaming"-style workshop. Invited thought leaders will be drawn from industry, academia, civil agencies, the military community, and space sustainability-oriented NGOs. Thanks to the longer format of this full workshop, and the expertise of the invited experts, the team will be able to explore the finer points of game theory and space exploration mission planning in greater detail – yielding better answers to our original question: will nations compete or cooperate? And can they be guided to those behaviors? The full workshop will generate two artifacts: a research-oriented paper that details the project methodology for future testing by others, and a white paper detailing the workshop proceedings, results, and any substantive policy recommendations.

2.3 Biospheres

The Biosphere concept proposed along the assessment is a semi-buried structure designed to reduce the impact of the extreme moon environmental conditions [1], while also ensuring the coexistence of humans and plants in a proper balance, in which the structure is made of a combination of pre-casted Earth materials and lunar resources, being the fundamental part the use of 3D printing additive manufacturing technologies [2]. It is a modular biosphere designed taking advantage of the orography to minimize costs and to sustain in a balance way up to 10 crew members together with crops and small animals, by arranging two different areas to house the different crops depending on their optimal development temperature. The modules can be linked to each other to recreate a bigger environment up to 5 modules and a total population of 50 crew members. Therefore, we have taken into consideration several factors in order to recreate a self-independent environment on the Lunar surface and Earth-like conditions. First of all, we have selected a crop selection which will provide adequate nutrition in terms of nutrient intake and benefits on the metabolic processes in order to fulfill the local activities [3]. Second of all, we have considered key factors to implement within the greenhouse such as temperature, partial pressure carbon dioxide, humidity, water pH in order to obtain an edible mass sufficient to the crew members' livelihood, which would meet the requirements for a daily intake of 3000 Kcal [4] and improve crop fertility by refining agricultural techniques. Furthermore, it has been proven that a proper nutrition in microgravity environments can combat the resulting damage of some metabolic processes, which may cause bone and muscle degradation or eye damage.

Third of all, the investigation also revealed how to enhance local resources for a long-term mission. In fact, an equivalent system mass analysis has been carried out in order to preliminarily quantify the overall shipped mass required to support the biosphere throughout long-duration stays and to assess the impact of different design choices on this key parameter, which is also an effective proxy for cost and logistic complexity. The analysis also allowed to compare the biosphere to a baseline reference case derived from existing greenhouse concepts. It turns out that the proposed biosphere could become more sustainable than the reference system in about 478 days. This is largely due to the assumption of in-situ manufacturing capabilities being available to fabricate structural parts, as well as to the possibility to source water locally. This is in line with the consolidated fact that long-term off-Earth presence necessitates the ability to leverage local resources.
Overall, the Biosphere team has identified several items for a research agenda targeting biosphere advancements. Some of these include:

- The need to significantly improve food productivity if lunar regolith is used as cultivation soil
- Use of 3D printing technologies for printing structures, ballistic protections and radiation mitigation.
- Further study of the orography and topography of the lunar surface to optimize the locations for human settlements.
- The necessity to improve off-Earth glass and light-weight metal alloys manufacturing
- The promotion of the extraction of liquid water, oxygen and nitrogen from regoliths during excavation activities.
- Broadening of crop selection and improvement of agricultural techniques to capitalize on the benefits of plants and improve the crew's quality of life.

2.4 Power

Robust and sustained access to power is vital for the development of every community. So far, each mission and - in the great majority of the cases - each robotic asset deployed on the Moon has been equipped with an individual power system. A similar approach would be definitely far from optimal for a scenario where multiple players perform long-duration, energy-intensive power activities. The possibility to plug into shared power generation, storage, or distribution systems would significantly decrease the launch mass per asset in the long term, as well as overall the development and operational costs per user. Also, scale-up efforts could be focused on a reduced set of larger power hubs, thus facilitating the adoption of new innovations as well.
As a foundational step in this direction, the Power Team within T.U.R.T.L.E. has surveyed the main power generation, distribution and storage technologies and carried out a trade-off analysis to identify the best options for the most relevant areas for future lunar activities, namely peaks of eternal light, permanently shadowed regions, dark side smooth terrains and pits [5]. Technologies were evaluated based on their performances under various sets of figures of merit which were specific for the four areas above, including interoperability. Subsequently, a sensitivity analysis revealed which fields of technological improvement hold the highest potential to drive the development of these technologies in the future, and hence their suitability for utilization in multi-actor scenarios. Table 1 below offers an overview of the main results of the trade-off study.

Table 1. Location-based recommended power technologies

Site	**Generation**	**Distribution**	**Storage**
Peaks of Eternal Light	Conc. Solar	Laser Beaming	Fuel Cells
Permanently Shadowed Regions	Nuclear (Kilopower)	Cables	Fuel Cells
Pits	Conc. Solar	Cables	Fuel Cells
Far Side Smooth Terrains	Conc. Solar	Cables	Fuel Cells

2.5 Dust mitigation

NASA's scheduled crewed mission to the Moon in 2024 will not only extend the realm of knowledge of the lunar surface but also pave a way for future crewed missions including crewed missions to Mars. However, in order to establish a safe and secure permanent presence on the surfaces of planetary bodies a holistic understanding of the challenge is required. One of these challenges is the electrically charged regolith that is caused by the lack of an atmosphere and increased solar winds. As space-faring nations aim to establish a sustainable human presence on the Moon by the next decade, a solution to deal with the charged lunar dust requires attention.

This project, hence, focuses on the design of a viable, innovative solution to mitigate the effects of lunar dust adhering to most surfaces, including scientific instruments, payloads, and other systems related to lunar missions themselves. The solution proposed in this project is twofold: it aims both to repel fine dust particles from multiple types of surfaces, and simultaneously to be able to collect them for further scientific investigations.

T.U.R.T.L.E.'s dust mitigation team has studied probable technologies and concepts to solve the challenge of dust mitigation and presented a feasible technology. In addition, the team believes that the need for performing specific tasks autonomously and supporting astronauts during their mission on the lunar surface will become a necessity.

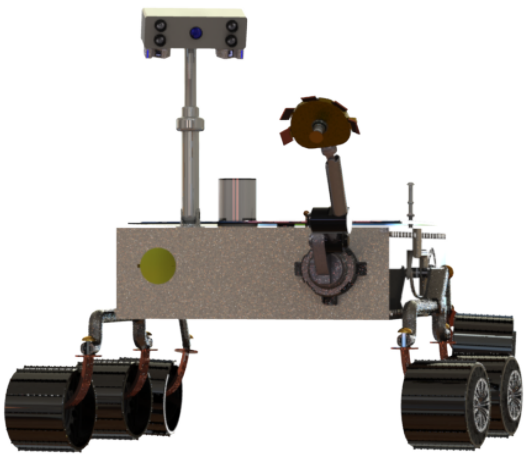

Fig. 1. 3D design of the dust removing vehicle [6]

For that purpose, the project proposes a preliminary design of a rover mission, as shown in Fig. 1. The rover's main focus is on protecting lunar equipment from the abrasive lunar regolith, and reusing it to support science experiments, and potentially provide key information to advance our understanding for infrastructure building on the lunar surface. This project also discusses the design of a laboratory for lunar dust processing. Overall, the dust mitigation team aims to solidify humankind's goal to build a sustainable infrastructure via such a mission concept.

3. Lunar Exploration Technology Adaptive Roadmap

The L.E.T.A.R. is conceived to be a flexible and evolvable framework where technology development programs are shared and improved on a continuous basis, fostered by transversal and multidisciplinary cooperation. This has multiple positive effects. On one side, such an environment would help shape a common vision and reciprocal understanding of various stakeholders' needs and objectives, paving the ground for constructive and inclusive dialogue. On another side, common or complementary technology development objectives could be found, allowing for significant optimization of time and resources. Furthermore, the iterative nature of the Roadmap allows constant updates and fast adaptation to both new insights and innovations.

So far, L.E.T.A.R. consists of several main pillars:

- A selection of suitable, *spaceport-grade* landing sites for lunar missions, with further insights on essential services, capabilities and legal frameworks to be implemented in order to ensure effective spacecraft servicing, traffic control, and improved logistics and safety.
- Self-sustaining biosphere concepts, designed to take advantage of environmental features and materials to maximize local resources utilization and minimize dependency from terrestrial support, as well as to be modular and scalable.
- A set of power generation, distribution and storage architectures, defined to match and suit environmental peculiarities and related needs, and to foster interoperability in view of the large number of potential users expected for future lunar surface activities.
- A dust-removing vehicle tasked to mitigate the omnipresent and potentially invalidating dust deposition problems virtually affecting all lunar assets, with the ability to serve as a mobile research facility.

The investigation framework and methodology leveraging game theory and interactive workshops set up by the Logistics and Infrastructure team can finally generate actionable intelligence on multi-stakeholder dynamics and behaviors, permeating and informing the general development of all the technical projects.

These items are fundamental and clearly interdependent building blocks for a comprehensive view of lunar technologies and their development.

From this baseline, several successive investigation steps can be devised, iterating on the current state and moving forward to an always greater degree of integration and interconnectedness driven by the holistic point of view offered by the T.U.R.T.L.E. research embedded in the L.E.T.A.R. ecosystem. These include, but are not limited to, the integration of power hubs with spaceports in support of spacecraft servicing and the definition of standard interfaces for visiting vehicles; the identification of landing sites with the highest potential to impact logistics and steer multi-actor activity towards cooperative strategies; the analysis of dust-removing vehicles operations within the broader context of spaceports servicing offer; the further evolution of dust-removing vehicles towards multi-purpose assets with inspection and maintenance functions; access paths and safe crew transport between spaceports and biospheres; inclusion of biosphere-related resources (food, plants, biopolymers, habitable space, human life support services) in negotiation processes and simulations.

Beyond this, T.U.R.T.L.E. and L.E.T.A.R. can be extended with new research themes and building blocks and participated by new entities. Some potential avenues for future developments include In-Situ Resources Utilisation technologies, with special regards to access and distribution, shared telecommunication and navigation systems, and surface mobility.

4. Conclusions

The work conducted by the TURTLE Group clearly shows the critical importance of concurrent and holistic technical research and technology planning for the development of a thriving future on the Moon. A clear trend emerging from these studies is the need to relieve spacecrafts and missions from the *all-in-one* design paradigm. To achieve the sustainable development of the Moon, lunar activities must be able to rely on a set of shared infrastructure providing essential services such as traffic management, power generation and fuel supply. We argue that this infrastructure should be made of specialized, interoperable, multifunctional building blocks servicing all lunar actors. In turn, this will free lunar missions and spacecraft from the mass and costs needed for these services, allowing them to focus their resources and capabilities on the achievement of their own goals. Needless to say, building this shared infrastructure and organizing its services will require appropriate arrangements covering the relevant legal, policy and economic aspects. Not by chance, the development of these very arrangements is at the core of recent diplomatic initiatives such as the Artemis Accords or the Declaration on the International Lunar Research Station. We recognize the critical importance of these initiatives both in the context of their own frameworks as well as for the global space community at large. At the same time, our work clearly shows that these “minilateral” initiatives are not enough to ensure the peaceful and sustainable development of the Moon. To achieve this goal, we need to kick off a multilateral and multistakeholder conversation bringing together all initiatives and actors around critical aspects for the practical conduct of lunar activities. LETAR is meant to drive the beginning of this conversation by identifying the practical needs shared by all lunar missions and offering potential technological solutions to address them. To this end, the TURTLE teams identified critical gaps and opportunities in current technologies to be addressed at multiple levels of analysis, delineating research domains with a multitude of intersecting needs and topics that can spur further research. We therefore encourage all like-minded entities interested in this conversation to engage us in any form or manner, for example during the congress. A vast landscape of opportunities can be disclosed after a first collaboration endeavor.

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