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Architecting Our Shared Lunar Future: Open, Dynamic, Participatory Roadmapping

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Our Return to the Lunar Surface Will Require New Modes of Collaboration

Last year we celebrated the 50th anniversary of the first landing of humans on the Moon. This historic achievement was the result of unprecedented coordination and collaboration among different actors on a vast scale. Their pooled resources, agility, experimentation, and creativity led to innovations and socioeconomic benefits that far outlived the Apollo mission itself. However, the unbridled success of Apollo didn't lead to a new era of lunar exploration. Once the flags had been planted in the lunar regolith, the U.S. government's love affair with the Moon was over, and without mission directives from the White House or NASA headquarters, the industrial ecosystem that grew out of the Apollo missions was left to pursue its own objectives.

Recently, public and private actors alike have set their sights back on the Moon. Unlike before, this generation's lunar exploration efforts will involve more private actors and many more space-faring nations than before. It is clear that such large scale and cross industry collaborations can generate radical innovations. How to encourage these diverse partners to come together, overcome differences in interests, and create an integrated, mutually reinforcing strategy for peaceful lunar exploration remains in need of both theoretical and practical advances. Pursuing these advances is both daunting and worthwhile because, after all, "we do this not because it's easy, but because it is hard" [1].



In this new age of lunar exploration -- with competing objectives and visions -- we believe the development of an integrated lunar surface strategy based on an open architecture is of paramount importance. There are several pillars of an open architecture that could fortify the lunar exploration ecosystem and enable a healthy, multilateral, and long-lived exploration exosystem. Examples of these pillars include: open information sharing tools, mechanisms, as well as convenings of fora for the community structuring and sharing of that information; open sourcing of hardware, software, and data; ecosystem-driven standardization of interfaces, hardware components, etc.; and convening collaborations to launch payloads that would be unreasonably expensive or risky for an individual organization.

Roadmapping is a “tried and tested” strategy employed by space agencies to envision a sustainable set of activities to enable mission objectives [2]. We believe an open, shared roadmap to further lunar exploration and development could be integral in accomplishing this -- on a global scale -- with input from a variety of actors from the public and private sectors to co-create and work towards a shared future on the lunar surface.

Designing for Collective Impact in Space Endeavours

Currently, the emerging lunar surface ecosystem does not have a clearly defined or unified goal. Most planned lunar surface missions are self-contained in terms of their physical presence and operational strategies [3]. Moreover, those missions most often optimize for isolated, rather than collective, impact [4]. In the commercial sector, traditional prime contractors and NewSpace¹ alike overlook the potential for collective impact because they are accustomed to focusing on independent action as the primary vehicle for securing space agency funding [4]. The lack of shared lunar surface infrastructure, such as power and communication systems, or broadly established precedents for considering the sharing of such infrastructure, makes the design of missions optimizing for collective impact still more difficult. Space agencies in turn judge each organization on its own potential to achieve impact, independent of the numerous other organizations that may also contribute to solutions.

Shifting from isolated impact to the collective impact needed to sustainably develop the Moon is not merely a matter of encouraging more collaboration or public-private partnerships - it will require a shift in the way we design and govern future

¹ “NewSpace” refers to the recent growth in the commercial space sector.



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exploration missions [4, 5]. Motivating dozens or even hundreds of organizations to work together — and making sure that projects will be developed in a way that optimizes shared value and benefits while minimizing shared risks and costs among all stakeholders — is extremely difficult when no one is in charge [6].

Top-down governance based on authority and control suffices when the scope is limited to one organization's sphere of influence. Alliances become transformational when their members commit to improving the whole system for everyone's benefit, and not just their own [7]. The collaboration needed to build a peaceful future on the Moon requires a departure from traditional hierarchical and linear approaches. Instead, it requires innovative and adaptive approaches that engage broad networks of diverse space and terrestrial stakeholders to advance progress toward a shared vision for permanent lunar surface infrastructure.

These tactics of building and mobilizing multi-stakeholder coalitions and alliances have been refined over centuries, particularly through advocacy campaigns, social movements, community-based development programs, and political parties [7-9]. What differentiates alliance-building in the context of large scale cross industry collaboration is the explicit goal of broad and long-range system transformation.

To illustrate how it can work, consider an example :

The landmark 2015 Paris Agreement committed 195 countries to a framework for action on climate change – including specific objectives for reducing greenhouse gas emissions, support for climate change mitigation, and a monitoring and reporting framework [10]. Advocacy and negotiations leading up to the Paris agreement engaged thousands of organizations internationally across government, industry, civil, academic, and religious sectors. A number of individual leaders within these stakeholder networks played crucial roles in building alignment, mobilizing action, and securing commitments. The most visible was Christiana Figueres, who led this historic process as Executive Secretary of the UN Convention on Climate Change (UNFCCC), establishing what many characterized as a new model of collaborative diplomacy – engaging a broad diversity of stakeholders in jointly developing solutions and commitments [11]. That model requires coordination as well as vision, trust-building, and innovation [7].

We can explore the application of similar strategies from examples such as these, among others, when designing a shared path forward towards lunar settlement.



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“We cannot impose our will on a system. We can listen to what the system tells us, and discover how its properties and our values can work together to bring forth something much better than could ever be produced by our will alone.”

– Donella Meadows [12]

The Case for a Dynamic, Collaborative Roadmap as the Backbone Platform Towards Lunar Settlement.

Now, imagine a knowledge-sharing tool and corresponding participation architecture to increase transparency and promote coordination among groups working on a path towards a sustainable lunar presence, enabled by innovative technologies, policies, and funding strategies. Collaboration will be imperative in cultivating a sustainable and peaceful lunar future. Any architecture must consider the expectations --both current and future-- and goals of many stakeholders, and should strengthen any interdependencies between them [13, 14]. At the level of national space agencies, a coordinated global exploration strategy must build upon the industrial competitive advantages of contributing nations, and also take into account export control regulations, as well as geopolitical considerations.

From a commercial perspective, economic development beyond low Earth orbit (LEO) will require market shaping and market co-creating policies [19], as well as increased funding for basic research and R&D investments. Many NewSpace companies have business models that make sense only when other, complementary business models or government incentives are already in place. The ambitious exploration objectives of private actors will be made possible only with public-private interaction and coordination of provision of services, physical interfacing, and infrastructure development. For example, the successful integration of in situ resource utilization (ISRU) into space architectures requires a collaborative approach towards exploration in order to achieve increasingly diverse mission objectives and enhanced mission sustainability, while overcoming the added mission complexity [15]. Moreover, Physical interaction or coordination among assets on the lunar surface will rely on the ability to operate within specific technical/engineering standards and mutually-agreed upon norms of behavior [3].

It is self-evident that this stakeholder coordination will depend on a foundation of trust and information sharing. At present, the most comprehensive collections of this information are presented in static exploration roadmaps, but they suffer major



limitations in their utility. Exploration roadmaps have historically been prepared through a process that does not involve all the relevant actors of the emerging space economy. The resulting roadmaps are large documents representing a snapshot of thinking and capabilities at the time of its release by a singular organization (e.g. [NASA Technology Roadmaps](#), [LEAG-LER](#), [Global Exploration Roadmap](#), [Luxembourg Space Agency Space Resources Value Chain](#)). In addition to their limitations in perspective, the format of these architectures disallows their evolution over time to incorporate new developments, preventing them from being a functional resource for supporting the space economy [16]. Furthermore, few, if any, of these roadmaps consider factors beyond science and technology objectives, making their perspectives thematically, as well as temporally, narrow [17]. While these limitations are broad and pervasive, they are not compulsory aspects of exploration roadmaps.

Now, we consider the collaborative creation of an open and dynamic online repository of key components required in a value chain that extends beyond LEO². These components could be portrayed by a modular structure that enables the exploration of different scenarios and solution sets; while revealing key knowledge gaps (SKGs) and leverage points. Such a roadmapping effort would incorporate existing content from agency and intergovernmental roadmaps into a dynamic web-based format that can evolve along with the developing ecosystem of lunar activities. This would be enhanced by the participation of the full complement of credible actors, seeking to balance proprietary and strategic interests with opportunities for collaboration and mutual benefit.

Developing a collective understanding of the lunar surface ecosystem would involve debating its boundaries, mapping its actors, missions, infrastructure elements, and dynamics, as well as considering the political environment around the system that influences it -- from institutional policies and incentives to personal choices and behaviors [7]. Articulating the role of power dynamics within the lunar ecosystem as well as identifying beneficiaries and those potentially at risk by those dynamics are important aspects of this roadmapping work. Exploring multiple potential avenues of lunar surface development and their implications, based on analysis and stakeholder experience, is key to shaping pathways to action.

Finally, this open roadmap could act as a backbone structure for collective impact, helping leverage transparency to create public discourse and a global identity around sustainable lunar surface operations, increasing public support, and creating

² Low Earth Orbit



a feedback loop to build a sense of urgency and accountability towards the public [18]

Designing for Participatory Roadmapping

The role of deliberative governance and participatory processes underpinning large scale collaboration is specifically emphasized in the academic literature [19]. Without strategic alignments and partnerships around purpose, the open architecture is likely to fall short of meeting its ambitious goals [7]. Galvanizing decentralized and open action across all relevant lunar actors will require several tactics to manage associated complexity and risk while ensuring a sense of mutual accountability.

What can we learn from existing structures designed for collective impact?

A growing body of literature discussing collective impact, adaptive systems design, and systems-level change highlights the need for a special type of an innovative interactive structure—called a backbone organization, cross-sector coalition, or partnership platform—to mobilize, support, align, and coordinate the efforts of stakeholders and organizations system-wide to accelerate progress and achieve scale [6, 20-27]. This type of organization³ is critical because most others lack the time, incentive, or credibility to do the job. This job typically includes:

- identifying relevant stakeholders and articulating the value proposition for them to work together;
- bringing stakeholders together across traditional sectoral boundaries⁴, creating a sense of inspiration and energy, challenging their biases and perceptions of one another, cultivating mutual understanding, respect, and trust while developing a common language;
- uncovering and promoting opportunities for stakeholders to collaborate;
- securing resources (financial and otherwise) for innovation and collaborative work, ranging from R&D to pilot/prototype projects;
- holding stakeholders accountable to one another by facilitating regular dialogue; hosting formal consultations; creating feedback mechanisms; helping stakeholders define mutually agreed-upon, dynamic indicators of progress; and pressuring them to measure and report;

³ Most of these large-scale leadership platforms are less than a decade old and their impact is still evolving. Much of this work is still relatively unknown or known only superficially to those engaged in collaborative systemic change efforts.

⁴ Important parameters: who has a seat at the table, what questions and concerns are sidelined, and what power asymmetries are shaping the terms of debate.



- enabling stakeholders to learn from one another by disseminating their approaches and lessons as well as facilitating peer-to-peer learning [18].

In the facilitation work done by backbone organizations, “the key is not so much to be neutral, but to maintain integrity”[4]. Certainly, backbone organizations must exercise visionary leadership and provide some amount of “push,” but the question is how. It is assuredly a long-term endeavor. In its collective impact work, FSG⁵, a mission-driven, global consulting firm, suggests that backbone organizations must be willing to dedicate a decade or more to advancing a systemic effort [30].

Finally, backbone organizations, along with other types of interactive structures and platforms, can only be effective in bringing about systemic change when supported by individuals as well as institutional leaders [32]. FSG points out that while this is a relatively new strategy for most existing leaders and institutions, “it can be a highly leveraged investment. A backbone organization with a modest annual budget can support a collective [process involving] several hundred organizations, magnifying the impact of millions or even billions of dollars in existing funding”[4].

Beyond Conferences, Towards Ongoing Collaboration

Adaptive Organizational Structure

In a complex and rapidly evolving world, a major challenge early in the roadmapping process is to define a long-term goal that is both ambitious and achievable. Coordinating the lunar surface stakeholders will require consistent investment of time, collective will, and ongoing facilitation. Collective impact alliances are often informal or self-organizing in their early stages, then grow to a scale and level of complexity that requires more formalized support. Developing a formal coordinating and governance structure too early in the process may constrain innovation and impose transaction costs on a fledgling network. One solution is to develop coordinating capacities in stages, starting with informal and flexible arrangements.

Establishing a Secretariat

Most large, global multi-stakeholder initiatives are supported by secretariats with established funding and governance structures. A secretariat toolkit developed by

⁵ FSG was founded in 2000 by Harvard Business School Professor Michael E. Porter and Mark Kramer to help foundations create more effective strategies and impact beyond their grant dollars.



the WEF New Vision for Agriculture initiative describes options and best practices for establishing a partnership secretariat [33] We envision the creation of a new, shared open architecture roadmap by a network of stakeholders both decentralized and coordinated. While capturing the output from existing fora that facilitate both formal and informal in-person interactions, an online, open tool will allow for rapid dissemination of discussions and knowledge, resulting in an evolving, frequently updated roadmap that is reflective of the current state of the industry. Eventually, this may evolve and be coordinated by a more formal secretariat.

Choosing a Focus; Increasing Fidelity and Actionability

In the first version of the roadmap, we could scopped-down the effort through choosing a focus. For example, a focus on roadmapping ISRU efforts. Focus is essential to elucidate key features of the architecture and create a robust tool to bring about the deepest and most lasting system-level transformation [7, 19]. ISRU and, more generally, space resource utilisation (SRU) describe the use of natural resources from the Moon, Mars, and other bodies for use *in situ* or elsewhere in the Solar System. Creation of a value chain around ISRU or SRU is seen as a foundational step in enabling sustainable future space exploration [15].

ISRU currently serves as the backbone for [NASA's Artemis 2024 program](#). Moreover, ISRU, in-space manufacturing, and in-space assembly are among the top priorities for government investment in the White House list of R&D priorities for the FY2021 budget [32]. Other agencies such as ESA, CSA, JAXA and UAE have recognised ISRU as an essential first-step in lunar exploration plans. There also exists a business case for commercial involvement in ISRU, and private industry has already begun investing in this area.

Already within the space community, a range of processes to produce usable resources have been proposed, such as water and oxygen production from lunar regolith, extraction of lunar ice and minerals, and construction of habitation elements by solar sintering and additive manufacturing. Practical and successful implementation of ISRU requires that all the stages of the life-cycle (prospecting, excavation, transportation, beneficiation, refinement, manufacturing and even service and end-of-life disposal) are considered. This requires a complete 'mine-to-market' type approach, analogous to that of terrestrial mineral extraction [15, 35].



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One of the key challenges in enabling the utilisation of space resources is the unique cross-disciplinary nature of SRU. It integrates space systems and safety, robotics and materials handling, beneficiation and chemical process engineering. This is underpinned by knowledge of lunar or planetary geology, mineralogy, materials science, and even legal aspects [15]. Combining such diverse fields in a coordinated way requires the use of an integrated architecture and value chain across a diverse range of stakeholders, and thus could serve as an ideal first case study for an open roadmapping project. Such an architecture could enable operations and comparison of SRU technologies while defining a global common terminology to be used across all exploration and resource utilization fields (in terrestrial and extraterrestrial applications alike).

There are many ways to create a shared roadmap of a complex system – ranging from interactive workshops using analog tools to sophisticated, computer-generated models. Some groups accomplish this mapping and information exchange purely through dialogue. Regardless of the format, the mapping process plays several vital roles in the crucial early stages of cross-industry partnership. It establishes a shared knowledge base, built on information contributed by all participants. It builds trust by providing a platform for every contributor's perspective to be shared. Furthermore, it surfaces shared interests, sometimes in unexpected ways, which can serve as building blocks for developing a shared agenda and robust strategy. While the process takes time, the unique value of the resulting product is well worth the resource investment when the roadmapping work is being done to describe a highly complex, adaptive system [7].

Shortcuts don't work when it comes to building genuine multi-stakeholder buy-in to a shared, long term vision -- this cannot be over-emphasized. However, the challenging work of building a shared vision and architecture at the outset pays off substantially in the long term. Compared to a unilateral perspective, multi-stakeholder involvement creates not only broader support, but also a more robust strategy, reflecting the full array of stakeholder knowledge and providing a much greater chance of long-term success for the initiative [20, 30].



Conclusion

The need for collective action and joint problem-solving is more important and urgent than ever if we are to create peaceful and sustainable lunar development. Coalescing the objectives of the diverse (public and private) stakeholders in the space industry is an undertaking that has yet to be achieved. Here, we propose a tool that will capture the evolving landscape of lunar exploration and development while offering a way of identifying shared objectives and goals, as well as potential gaps or roadblocks, on our path towards lunar settlement.

Although ambitious, the very nature of an open roadmap is dynamic and flexible. It could foster information sharing ranging from payload designs, to mission operations, all the way to a permanent lunar public infrastructure and associated cooperative frameworks. The success of such a roadmap would depend upon broad acceptance, participation, and multiple implementation scenarios. Hopefully, its adoption would further encourage collaboration across industries and borders.

The literature on backbone organisations offers a set of tools, tactics, and strategies that can help address the complex challenges we will face while building an inclusive future on the Moon. In spite of the youth of backbone organizations as a conceptual interactive structure, the great potential value of applying this approach more broadly is worthy of further exploration and development.

Studies of the social dynamics of international collaborations — from setting research agendas to allocation of intellectual-property rights — could help reveal hidden power imbalances that are likely to influence who benefits from the open architecture research and lunar surface development, as well as who does not.

"Going to the Moon required romantic madness in order to believe that it could be done, and practical genius to make it happen. Landing on the Moon is still the single greatest achievement in history, and one dedicated to "all mankind." Yet it was also an act of single-minded determination and it took wild, dedicated individuals to achieve it."

- Stranger Than We Can Imagine



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