SEPTEMBER 2025

SOLVING THE PUZZLE OF EVOLVING SPACE ECOSYSTEMS

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Summary

The space ecosystem is becoming crowded as world governments and commercial organizations continue to develop new civil and military space programs. With the variety of players racing to accomplish their own goals in isolation, the natural evolution of the space ecosystem can result in duplicated efforts and other obstacles. To combat these inefficiencies, stakeholders can integrate a collaborative space enterprise approach, using the triquetra framework, to establish and facilitate an evolving space ecosystem. This paper discusses the need for an evolving space ecosystem planning effort and proposes incorporating coordinated planning and advanced engineering solutions among commercial and government stakeholders to maintain a global advantage in space.

> *"The long-term policy of sustainable space exploration and development depends on alignment with enduring national interests such as a security, economic growth, scientific advancement, and a stable international environment. As new information comes to light and new experiences are gained, the United States should be prepared to adapt to new opportunities and risks…The international environment is dynamic and influenced by competition an threats to the space capabilities on which we rely. Consequently, it is important that U.S. space activities across the civil, commercial, and national security sectors be coordinated at the highest levels and in an integrated manner to advance our holistic interests and those of our international allies."*
>
> *–National Space Council, July 2020*

Introduction

It's 2035. A bustling cislunar ecosystem teems with commercial lunar landers, robotic rovers, U.S. government exploration hubs, power stations, and communication relays, while low Earth orbit (LEO) buzzes with orbital factories, automated servicing platforms, and thousands of domestic and international satellites delivering global connectivity. This dynamic ecosystem falters when a major provider of critical utility infrastructure exits abruptly, crippling essential power and communication networks. The disruption threatens national exploration missions and global space stability. As commercial and government actors race to dominate expanding frontiers in space, the pressing need for a robust, adaptive framework to orchestrate and stabilize an evolving space ecosystem and ensure its sustainable future is essential.

Space ecosystems, evolving in operational domains, including LEO and cislunar space, are comprised of intricate networks of interdependent systems. Driven by technological advancements, market dynamics, and geopolitical shifts, a space ecosystem inevitably evolves as the systems interact and adapt. Fueled by the influx of new actors and exit of others, the pace of evolution has accelerated over recent years, creating a vibrant yet chaotic landscape. Different actors have unique approaches to a wide variety of goals. Natural evolution of a space ecosystem can result in inefficiencies, duplicated efforts, safety issues, and obstacles. Consistent with national space policy and goals, it is in the best interest of space actors for a space ecosystem to evolve in ways that support stability and sustainable growth.

Space Ecosystem: Complex set of linked space systems with symbiotic and other ecosystem attributes and the operating environment where they interact.

Evolving Space Ecosystem: Transformations to complex set of space systems over time as a function of changes in operating systems and functions.

A key driver of rapid evolution of a space ecosystem is increased deployment of commercial solutions for civil and military space programs, domestically and internationally. The "commercial first" focus of the National Space Policy, released on December 9, 2020, encourages government leverage of commercial solutions and strengthening of the space industrial base. The cislunar ecosystem has more than 10 U.S. government organizations and more than 80 companies collectively investing billions per year to develop and deploy capabilities aligned with 12 infrastructure layers.[1] Across multiple nations, space strategies call for leveraging commercial solutions.[2] Private investment, totaling scores of billions of dollars across thousands of companies, has fueled innovation in commercial space capabilities. These commercial capabilities are being deployed to operate in a space ecosystem, alongside government purpose-built systems, and leveraged for civil and defense use.[3]

Like biological ecosystems, a space ecosystem will evolve through interactions. For long-term growth and sustainability, coordination among commercial and government owners and operators is essential. Research shows that symbiotic relationships in an ecosystem support long-term market acceptance and expansion as well as enable ecosystem sustainability.[4] On the other hand, isolated products and services trend toward obsolescence. Increasing the number of actors and products often increases ecosystem resiliency to changing markets and economic drivers. When actors can act in concert, an ecosystem benefits over the long-term through interoperable and inter-related capabilities combined in different configurations to fill a variety of missions.

While enabling on-ramping of new players, innovative technology, and operational capabilities, government organizations have the challenge of solving the puzzle of how to leverage commercial capabilities in appropriate configurations to accomplish national missions. Government program leaders can benefit from a common environment to conduct engineering needed to fit commercial capabilities together like pieces of a puzzle. Similar to how urban master planning promotes a coordinated evolution of industrial and residential ecosystems, space ecosystem master planning, coupled with engineering for interoperability, helps ensure current and future space capabilities work together and do no harm to others in the process.

Benefits to cislunar master planning for the deployment of space have been outlined in an earlier paper.[*] This follow-on paper looks at the construct of evolving a space ecosystem in cislunar, LEO, and other space operating environments, going further to define a coordinated engineering approach to enable stable and sustainable growth. Enabled by the agility of digital engineering, finding whole-of-government solutions to achieve national goals in space is possible from a combination of enterprise engineering and integration with ecosystem

[*] Prior research can be found at https://csps.aerospace.org/papers/charting-course-through-cislunar-master-planning by Cris Guidi and Ron Birk "Charting a Course Through Cislunar Master Planning," The Aerospace Corporation, Center for Space Policy and Strategy, 23 June 2022.

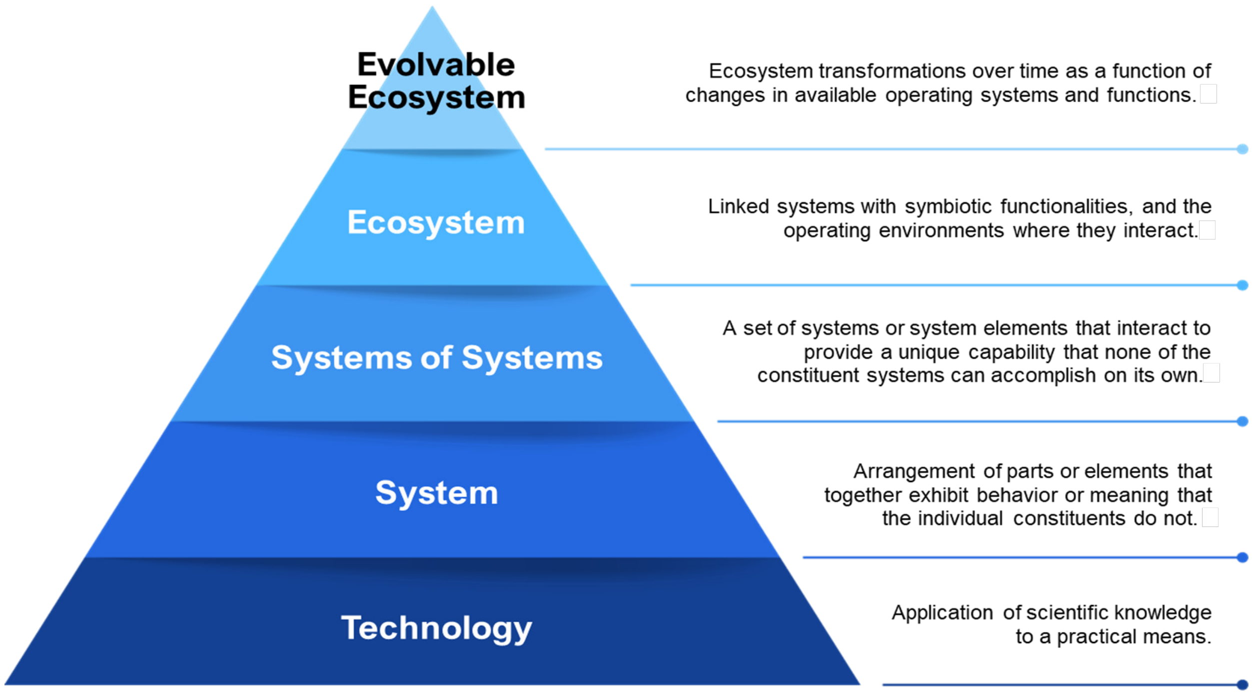

Figure 1: Increasing levels of integration.†

engineering. By integrating these three engineering disciplines into a cohesive approach—termed the *triquetra* framework—stakeholders can plan for changes, identify and address gaps, and meet critical needs in the context of a dynamic evolving space ecosystem.

The Hierarchy of Integration: From Systems to Evolvable Ecosystems

A space ecosystem is comprised of interconnected systems and system of systems (SoS), in a shared operating environment. As technologies advance, space environments change, and actors enter and exit, an ecosystem transforms over time, introducing new capabilities and leaving gaps as they come and go. Figure 1 illustrates the progression from a base level of individual technologies, up through a systems level, to higher orders of integration—each with distinct approaches to acquisition, program management, and engineering when it comes to supporting national mission goals and objectives.

Moving up the levels of the pyramid, the degree of oversight by any single organization narrows with more focus on interplay among interconnected capabilities. At the base, a broad array of technologies is developed by individual organizations. For a **single system**, the systems engineering and integration (SE&I) focus is on designing and managing a single, cohesive element for a purpose under single governance. For example, SE&I for a Landsat spacecraft is conducted under centralized control focused on a unified purpose of moderate resolution land imaging. Acquisition at this level involves detailed requirements flowing

† Note: Figure 1 references the INCOSE definitions of system engineering and SoSE as described in https://sebokwiki.org/wiki/SystemsofSystems(SoS). Figure 1 includes crafted definitions for space ecosystem and evolving space ecosystem by the authors of this paper as no official definitions were available at the time of publication.

down to multiple integrated technology-based solutions.

Moving up the pyramid, **system of systems engineering (SoSE)** operates at a higher level of interoperability and complexity, coordinating multiple independent systems under a single authority to achieve a unified objective, emphasizing interoperability. The NASA Artemis program exemplifies this, integrating a Space Launch System, Orion crew capsule, and commercial human landers to enable human lunar landings for exploration. SoSE ensures these different organizations' systems work together seamlessly with standardized interfaces, including communications, power, data, and docking. The focus of acquisition of SoS shifts from subsystem specifications to system-level requirements, allowing flexibility in how each element meets its role while integrating together to deliver unique capabilities that none of the elements can deliver on their own.

Up another step in the pyramid, at the **ecosystem** level, the degree of organizational oversight narrows. A space ecosystem is comprised of networks of diverse systems from commercial and government providers, linked to form a mutually beneficial infrastructure without a controlling authority. Here, the role of ecosystem engineering is to manage the interplay of decentralized, market-driven capabilities for an intended mission. In delivering goals and objectives for national missions, the role of ecosystem engineering is tantamount to an orchestration of distributed capabilities. Solutions formed from capabilities operating in an ecosystem require planning, configuring, and operating a multitude of space systems, orchestrated and engineered to deliver reliable, resilient national missions together. As noted in *Defense Reformation*, the fifteenth thesis statement argues that "Reference architectures can't be created, they emerge," which suggests complex architectures that leverage innovation must emerge through iterative integration and interoperability, and not through rigid government reference architectures that provide detailed, upfront specifications.[5] Quite a challenge for national missions for space exploration that are designed to solve the nation's hardest problems, such as Artemis.

At the apex of the pyramid is the evolvable ecosystem, dynamically adapting to space capabilities entering and exiting over time. This level transcends static configurations within the purview of primary governance. This level is characterized by continuous change. In the context of evolving ecosystems, engineering solutions for national missions involve periodic refresh and expansion, coupled with proactive gap-filling of capabilities and services as actors enter and leave the stage.

Challenges of Uncoordinated Evolution

Like an ecological ecosystem, a space ecosystem evolves through effects of multiple forces. While adapting to market shifts, national politics, geopolitical dynamics, and advancements, commercial actors compete with other providers for customers within a space ecosystem. These adaptations can have positive and negative consequences.

Unguided evolution of space ecosystems, while dynamic and potentially vibrant, poses significant risks. The following examples highlight the significance of impacts of changes across the private sector on government space missions that leverage commercial solutions. Impacts will continue to grow commensurate in response to national policies and strategies that prioritize government use of commercial space capabilities.[6]

- Company operating a system or service for the government goes bankrupt (i.e., Virgin Space)

- Demand for capability changes and/or is not present in time to sustain the capability for a national mission (i.e., SST Concorde retirement)
- Company acquisition/merger impacts contracts (i.e., L3Harris/Aerojet Rocketdyne, Maxar/Redwire)
- New entrant augments current capability in the ecosystem, altering best approach to deliver space functions (i.e., heavy lift launch including Starship ad Space Launch System)
- New demands and capabilities emerge that can be applied to a national mission (i.e., LunaNet communications for cislunar domain)
- Changes in capability reduce costs—a company evolves a new system to adjust to market forces (i.e., Falcon 1 to Falcon 9)
- Technology/system evolves to meet functional needs of other systems (i.e., in-situ resource utilization)

Without deliberate guidance, natural evolution can disrupt national missions dependent on leveraging commercial capabilities. Government agencies, tasked with leveraging commercial capabilities for missions intended to solve the nation's hardest problems, such as Artemis, must tackle this challenge. How does a government organization solve the puzzle of how to integrate diverse, rapidly evolving systems while ensuring safety, efficiency, and mission success? Absent the application of engineering to identify and mitigate risks, impacts can include lack of interoperability, duplicated efforts, inefficiencies, and safety hazards.

Guiding Evolution within an Ecosystem

Several ways for a national government organization to influence ecosystem evolution include policy, acquisition, and SE&I.

Policy can promote cooperation through top-down government guidance. Using the cislunar domain as an example, the 2024 *National Cislunar Science and Technology Strategy* emphasizes coordination for cislunar infrastructure, including communication, navigation, power, and mobility.[7] An example of government acquisition is the Department of Defense's Defense Advanced Research Projects Agency (DARPA) 10-Year Lunar Architecture (LunA-10) Capability Study, launched in November 2023. LunA-10 focused on creating monetizable services from 13 companies for future lunar users to develop shareable, scalable, resource-driven systems that complement NASA and international lunar investments, moving away from individual efforts with isolated, self-sufficient systems.

Coupling systems engineering and integration objectives with acquisition can ensure select functions of capabilities are interoperable. Commercial development does not inherently result in mutually beneficial and interoperable systems and functionality. An example is the case of NASA's Boeing Starliner Crew Flight to the International Space Station in June 2024, in which two astronauts, Butch Wilmore and Sunita "Suni" Williams, found themselves without a viable return to Earth for months longer than intended. The Starliner experienced thruster failures and helium leaks leading NASA to deem the capsule unsafe to return with the crew. NASA had an alternative vehicle to go to ISS with the SpaceX Crew Dragon. However, there was no requirement for compatibility of the space suits on the Boeing Starliner and SpaceX Dragon capsule. The suits had different connectors for life support, communication, and power that were not interchangeable between the two spacecraft systems.[8] This example highlights the benefit of considering evolved acquisition, management, and engineering approaches to foster evolution of space ecosystems.

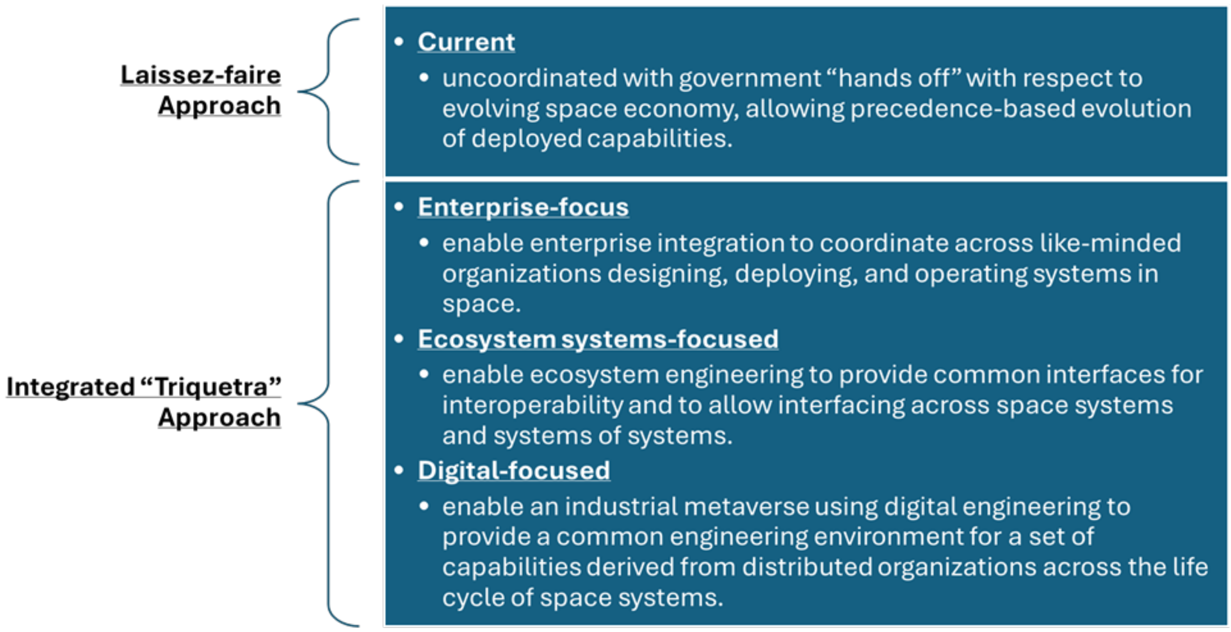

Figure 2: Ecosystem evolution orchestration options.

In the context of space ecosystem evolution, this paper focuses on guiding actions to enable government missions by applying an evolved set of SE&I approaches. Space-faring government agencies establish technical baselines of bespoke and commercial capabilities integrated to meet given mission needs, then monitor and adapt to changes to ensure continued performance of their national missions. With hundreds of commercial systems deployed into LEO and cislunar space, there will be multiple potential configurations for combining systems to deliver solutions. Policies and practices can guide actions to establish standards for common engineering environments. Common engineering environments can be used to plan, and then verify and validate, interoperability and "do no harm" analyses between and among space capabilities. Applying these guiding actions can lead to both increased commercial activity and enable government organizations to harness the benefits for national security and exploration.

Piecing Together a Moving Target

Experience suggests it is not feasible to accurately predict an exact path of evolution for an ecosystem. As a space ecosystem becomes more complex, tracking, understanding, and predicting how changes impact interdependencies across the entire ecosystem poses significant systems engineering challenges. Maintaining a healthy and robust solution from the set of systems requires proactively addressing shortfalls and filling gaps, as in the case of space suit interfaces. There are multiple approaches to apply engineering to orchestrate leveraging capabilities within a future space ecosystem, which are noted in Figure 2.

Continuing the current laissez-faire approach to space ecosystem development will likely result in a very dynamic, at times chaotic, evolution, affecting the stability of solutions. Often favoring "first to market solutions," a laissez-faire approach lacks interoperability standards for data exchange, or mechanical, electrical, and thermal interfaces. Without a guiding policy or strategy in the national interest, this approach could foster growth in *certain* space activities based on market forces, while curbing the ability of government space missions to leverage varied commercial capabilities for national missions. This is multiplied at the international level where the behavior of different countries and their private sectors could lead to a patchwork of standards, norms, and practices leading to potential encroachments among stakeholders.[9] In contrast, professional organizations such as the American Institute for Aeronautics and Astronautics (AIAA) and trade associations such as the Consortium for Execution of Rendezvous and Servicing Operations (CONFERS) can help coordinate standards across the enterprise to enable systems to safely and sustainably inter-operate without causing harm, such as for rendezvous and proximity operations using prepared Free-Flyer Capture and Release.[10]

An analogy for the challenge of using a wide array of space capabilities to engineer solutions for national missions can be represented in the context of solving a complex 1000-piece puzzle where the puzzle pieces are changing.

The Triquetra Framework: An Evolved Approach

Elements of the approaches described in Figure 2 can be combined into a comprehensive approach termed the "triquetra framework." The triquetra engineering framework synthesizes enterprise integration, ecosystem engineering, and digital engineering to coordinate solutions and leverage capabilities across a space ecosystem. By applying complementary systems engineering approaches, the triquetra framework goes beyond a traditional value chain to applications for a *value constellation*. Coined by Kees van der Heijden in 1993, a value constellation takes the concept of a value chain into a third dimension that is a dynamic, interconnected network where various entities collaborate to create, deliver, and capture value.[11] While the space domain does not currently benefit from a robust value constellation, this triquetra approach is a way to get there. The triquetra approach, illustrated in Figure 3, is characterized by a continuous process emphasizing interconnection and interdependence to orchestrate solutions through ensuring adaptability, efficiency, and resilience.[‡]

Enterprise integration coordinates stakeholders—government agencies, commercial firms, and international partners—to align plans, identify gaps, and ensure operations "do no harm." Ecosystem engineering ensures systems, such as launch vehicles and satellites, interoperate seamlessly while evolving and adapting to market-driven changes. The third element, digital engineering, employs digital twins, AI and cloud-based models, to simulate system interactions, creating a "space industrial metaverse."[12] This enables rapid testing, as in modeling a commercial rover's integration with NASA's lunar surface operations, predicting impacts of changes like power upgrades. The triquetra framework enables adaptability to both anticipated and unforeseen changes, maintaining mission performance of solutions comprised of capabilities evolving in complex ecosystems.

[‡] The triquetra is an ancient symbol characterized by three interlocked geometric shapes, forming a design that resembles three overlapping arcs or loops.

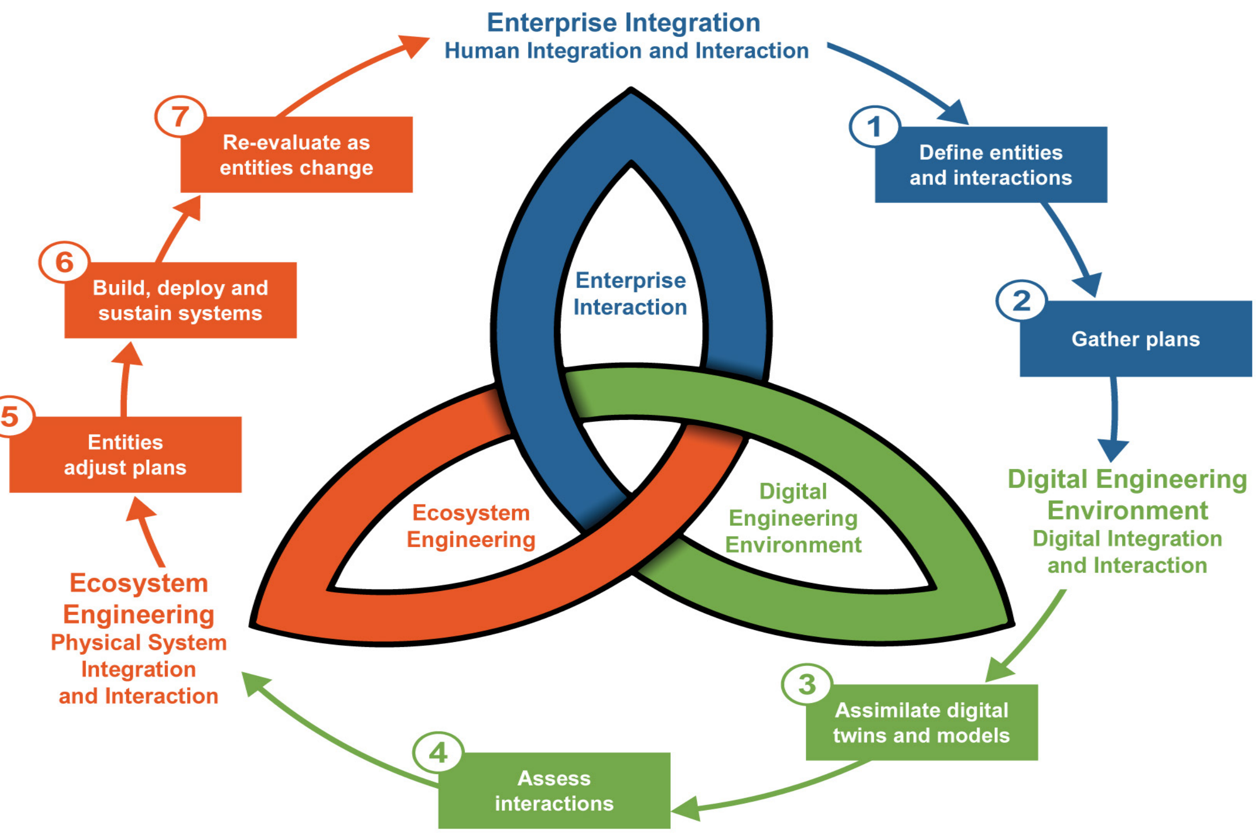

Figure 3: Continuous flow among enterprise integration, ecosystem engineering, and digital engineering.

Expanding on these three areas provides insights into benefits of applying the framework and impacts of not doing so.

Enterprise Integration Loop

Enterprise integration coordinates like-minded organizations to design, deploy, and operate space systems through enterprise integration enhancing collaboration across stakeholders.

NASA's Commercial Lunar Payload Services (CLPS) program could benefit from enterprise integration coordinating basic infrastructure, including communications and navigation to support lunar landers.[13] Enterprise integration can be conducted through intentional coordination, as well as orchestration and enhanced public-private partnerships. Implementing the approach can address shortcomings by expanding capabilities to support multiple agencies, resulting in maximized efficiency, reduced cost, and enhanced innovation through shared investments and multi-use capabilities.

Ecosystem Engineering Loop

Ecosystem engineering provides common interfaces to ensure interoperability across physical space systems and SoS, enabling seamless interactions.

The expectation systems operate without negatively impacting each other requires ongoing re-evaluation to account for interdependencies and changes over time. Unlike traditional SoSE that operates under centralized control, ecosystem engineering addresses decentralized systems that evolve independently and are not overseen by a single authority. Changes, such as system upgrades, new technologies, or market-driven shifts, must be considered. For instance, to maintain a technical baseline for a government mission, stakeholders must track changes to systems to ensure continued interoperability with other systems and services. A notable example is NOAA integrating data from a private company where the metadata format must be maintained to avoid disrupting weather forecasting models.[14] Ecosystem engineering also involves integrating new technologies and systems into the ecosystem. Emphasizing interoperability and modularity, approaches like the Modular Open Systems Approach (MOSA) allow independently developed systems to work together seamlessly. By fostering compatibility and adaptability, ecosystem engineering ensures evolving systems contribute to a resilient and cohesive space ecosystem.[15]

Digital Engineering Loop

Digital engineering can be applied to create a "space industrial metaverse" as a common engineering environment for testing and simulating capabilities derived from distributed organizations across the life cycle of space systems.

Digital engineering leverages digital models and data within a cloud-based infrastructure to streamline the design, development, and life-cycle support of systems, enabling engineering at an enterprise-wide scale.[16] These digital models, including digital twins, can serve as virtual testbeds and proving grounds, offering insights into the performance and interactions of physical systems while identifying potential conflicts or hazards. Operating in a digital environment enables harnessing the power of AI to rapidly analyze highly complex space systems, improving understanding and efficiency.[17] It also ensures access to current, consistent data, supporting informed decision-making and operational activities.[18] Practical applications of digital engineering include modifications to system form, fit, or function, such as adjusting the size of a launch faring, increasing power voltage, or transitioning from radio frequency to optical communications. By readily facilitating adaption to change, digital engineering enhances adaptability and resilience of space ecosystems.

Space Industrial Metaverse: An interconnected, immersive digital environment that mirrors and interacts with real-world space enterprise processes, systems, and assets, leveraging technologies like digital twins, augmented reality, virtual reality, artificial intelligence, and the Internet of Things (IoT) to enhance productivity, collaboration, and innovation in industrial settings.

The Triquetra Approach

The three loops—enterprise integration, ecosystem engineering, and digital engineering—share common themes: understanding system interactions, anticipating changes, reevaluating configurations, and adjusting. These themes reflect a continuous, dynamic process symbolized by the triquetra. Changes within a space ecosystem are not limited to the introduction of new actors, technologies, or systems, but also encompass the aging, evolution, and degradation of physical systems over time. Some changes are predictable, while others are unforeseen. A digital engineering environment enables stakeholder organizations to continuously update system models, reflecting these changes before they lead to operation or mission degradation. This environment also provides real-time performance assessments and predicts the ecosystem-wide impacts of modifications. Given the complex interdependencies within space ecosystems, the triquetra approach offers significant advantages for managing intricate, expansive, and long-term effects of changes on space endeavors. It facilitates a deep understanding of specific technical baselines within the context of evolving ecosystem performance. By integrating these three loops, the triquetra approach ensures space ecosystems remain adaptive, efficient, and resilient, capable of addressing both anticipated and unexpected challenges effectively.

Implementing the Triquetra: A Notional Seven-Point Cyclical Plan

As stated above, an evolving space ecosystem has no one decision-making body. So, for governments to harness capabilities for national missions, there must be a common understanding amongst participants, including the U.S. government, industry, and other space faring nations. There is a need to better harmonize the community through the triquetra approach using enterprise integration to converge stakeholder organizations to coordinate their plans, ecosystem engineering to ensure the

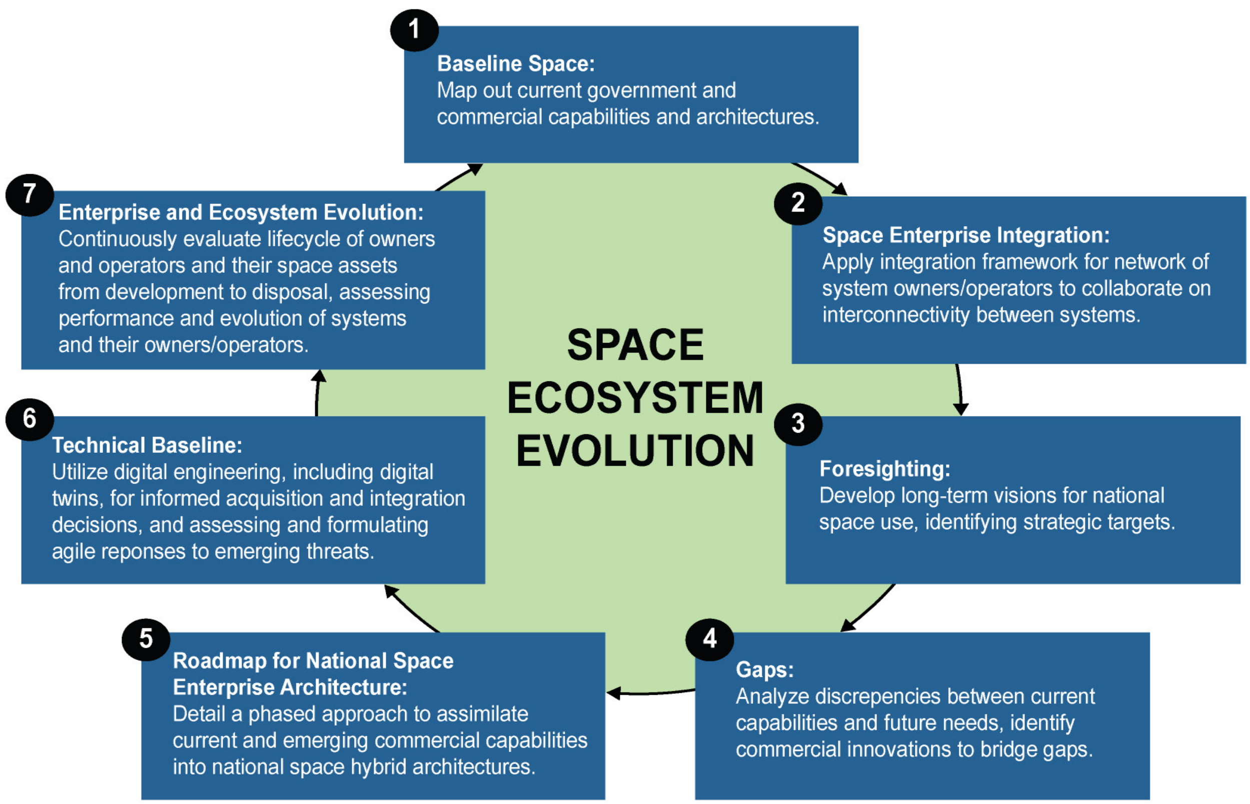

Figure 4: Notional seven-point cyclical plan for national space ecosystem evolution.

systems and services fit together into coherent configurations, and a digital engineering environment to understand the interactions, interdependencies, changes, and consequences to better inform decisions.

To operate the triquetra framework, the U.S. government and its allied partners can implement a seven-point cyclical plan as a circular process fostering continuous adaptation, as depicted in Figure 4. First, stakeholders assess available systems, cataloging commercial and international capabilities, such as CLPS landers or ESA's cargo modules. Next, stakeholders identify mission needs, aligning with national priorities like Artemis lunar landings. Coordination follows, convening government, industry, and allies through collaborative forums, as seen in the Artemis Accords' series of multilateral arrangements made between the United States and other world governments. Defining interoperability standards ensures interoperability, such as for data exchange or mechanical interfaces. Digital modeling then simulates ecosystem configurations, using digital twins to identify gaps or performance issues, as additional assets come into play or are retired. Validation through lab tests or simulations certifies mission readiness. Finally, continuous monitoring tracks changes—bankruptcies, new entrants, or system degradation—and updates digital models to maintain performance. This cyclical plan is rooted in the triquetra principles. By iterating through these steps, stakeholders can adapt to the dynamic nature of the space ecosystem, ensuring sustainability and mission success.

Conclusion

This is a call to action. The U.S. government and its allies must act decisively to optimize the approach to leverage capabilities in evolving space ecosystems to deliver national security and economic security. Adopting the triquetra framework—incorporating enterprise integration, ecosystem engineering, and digital engineering—can be essential to navigating complexity and change. Stakeholders should implement the seven-point plan, leveraging domestic collaborative forums for space, the Artemis Accords, and other international partnerships for master planning. Investing in digital tools, such as AI-driven digital twins and a space industrial metaverse, is a dimension of the triquetra framework to enable collaborative planning and advanced engineering to model and simulate interactions among systems ensuring mission success, resilience, and innovation. These steps will position the U.S. government and allied organizations to maintain a global advantage in space.

Reflecting on the history of space development can serve as a catalyst for stakeholders to rethink how space projects are developed, managed, and integrated into broader space ecosystems. While past space endeavors and achievements were significant, the future of space operations require a fundamentally different approach. The triquetra framework fosters continuous engagement across industry and allies, transcends the limitations of legacy methods, and transitions towards a dynamic, integrated approach to national space solutions that embrace complexity and change. For government organizations, the approach embraces "commercial first" policies enabling efficient integration of commercial capabilities while maintaining control of the government mission. The industry benefits from clear guidelines, including interoperability standards and access to government requirements, fostering market planning. This approach fosters a unified vision where coordination across varying organizations, interoperability of systems, and the use of digital tools for continuous improvement facilitate stability and sustainability in the context of innovation across an evolving space ecosystem. The approach aligns with needs to advance policies, acquisition strategies, and engineering practices. Such alignment with an evolving space ecosystem positions the United States and its allies to navigate the complexities of continuous change with agility and foresight.

As capabilities across an ecosystem evolve, structured engineering approaches can leverage rapid response to changing space capabilities. The triquetra framework can significantly advance national and economic security. A collaborative space enterprise integration approach can foster a community where innovation can thrive, leading to a sustainable and prosperous future in space. This strategic shift towards harnessing benefits of an integrated, dynamic space ecosystem model promises to enhance our capabilities, ensuring the United States and its allies can sustain space leadership into the future.

Acknowledgments

The authors would like to thank Craig Lindsay, Lake Singh, Matt Ferringer, Richard Deakins, Emaan Osman, Torrey Radcliffe, Stephen Lutton, and Dennis Paul, among the experts, officials, and colleagues who participated in discussions to contribute to the foundation and review of the paper with insightful comments, and to Katherine Melbourne and Colleen Stover for valued editorial support and advice. Finally, thanks to Julia Kopischke and team for the cover design and creating the graphics, and Adam Glover and Denise Betts for final edits and layout.

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