An Integrated Strategy for Growing the Space Economy

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We describe an integrated strategy for advancing and growing the global space economy from its current state of being "linear" to becoming "circular" and ultimately transforming it to be "regenerative". Linear space economy refers to a "take-make-dispose" approach while a circular one incorporates reuse, repair, and recycle techniques to cut demand for materials, especially rare minerals, and lower the overall costs. Ultimately a regenerative space economy couples a circular approach with resource generation in-orbit and on other planetary bodies, designed to become less dependent on Earth and eventually becoming self-sufficient, paving the path to a sustainable and permanent presence in space. This strategy relies on five interdisciplinary pillars: 1) modularity, 2) standardization, 3) interoperability, 4) maintainability, and 5) resources generation. The first three are the initial foundational pillars for advancement and growth of space economy since they enable a "plug-and-play" approach that is flexible, reusable, and ultimately more affordable by allowing subsystems, payloads, and even the entire satellites to be rapidly assembled, upgraded, repaired or replaced without the need for new design, significantly reducing non-recurring engineering and production costs. To develop a circular space economy, space systems must be designed to be maintainable so they can be repaired and upgraded. The last pillar, ability to generate resources, is crucial for expeditions beyond LEO to cislunar space and Mars. As distance from Earth grows, Earh-independence in operations and servicing becomes a crucial factor in achieving permanence and sustainability in space. We show how elements of this approach helped propel marine commerce and satellite telecommunication industries to phenomenal growth. We then offer a path to execute this strategy to successful implementation by discussing an industry consortium approach, and considerations for R&D investments, enabling policies, regulations, and workforce development.

I. Space Economy by the Numbers

The space economy is often defined by goods and services that are developed in support of space-based activities. The primary industries supporting space economy include manufacturing, construction, retail trades, information systems technologies, professional and business services (including R&D, engineering and technical services, education) and government (military and civilian agencies plus federally funded research and development centers or FFRDCs). Examples of space-based products and services include manufacturing of space vehicles, launch facilities and infrastructure, telecommunications and broadcasting means both on Earth and in-orbit, navigation services

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including GPS, as well as supporting products and services such as insurance, software, and project management, etc.

The space economy has been steadily growing in the past few decades, especially in most recent years due to significant interest and investments by the private sector. While traditionally the bulk of space-related global investments have been made by the public sector (primarily governments and space agencies), the private sector investments have been rising steadily in recent years fueled by the venture capital industry. According to the 2025 ESA Report on Space Economy [1], worldwide public investment in space in 2024 (~$146 billion) grew by 9% over previous year while the private investment in space (~$8 billion) grew by 20%. In 2025, private investments grew approximately 50% compared to prior year, to $12.4B [2], indicating the significant momentum in private space funding. The United States dominated private sector space investments providing about 60% of the global funding ($7.3B). The total investments are primarily driven by launch services, defense related programs such as the Golden Dome initiative in the U.S., and integration of AI into space hardware and software. According to Novaspace [3], defense related spending accounted for 54% of global spending, surpassing civil space applications. Space infrastructure is increasingly being viewed as strategic national priority to secure geopolitical advantage around the world alongside land, air, and maritime. Other areas of interest include space tourism, energy generation, advancements in biomedical and material science and technologies, to name just a few. These investments are expected to grow even more rapidly due to upcoming innovative opportunities in the future. Therefore, it is quite timely to devise, plan and implement an integrated approach for achieving a robust and resilient space economy efficiently and in a timely manner.

II. The Vision of the Future Space Economy

In the LEO environment, the aim of space economy is to make possible what is impossible on Earth through new frontiers in research and development (R&D) in microgravity conditions of space. These include:

1) Manufacturing of high-tech materials such as fiber-optics, ceramics and crystals, pharmaceutical products for use in energy, mobility, communication, and health sectors. Examples include bifluoride glass materials, high capacity and very long fiber optics such as ZBLAN.

2) Bio-fabricating organs such as lung, heart and liver tissues with the aid of 3-D printing which is difficult or impossible to do on Earth.

3) 3-D printing and manufacturing of microsatellites, instruments, and other space-based systems components, to overcome limitations due to faring envelopes and lift capacity of Earth-based launch vehicle systems.

4) Manufacturing of super-alloys, reinforced ceramics for heat resistance, large-scale solar arrays for energy production and long-duration space flight.

5) In-space development of self-healing and self-repairing systems based on a combination of 3-D printing and robotic technologies to avoid long delays due to deployment and avoiding risk of loss from Earth-based launches.

6) Maintaining and extending life of satellite systems by refueling (e.g. Northrop Grumman), developing in-space repair tools, active orbital debris removal, and recycling material resources in space (e.g. ThinkOrbital, Astroscale, ClearSpace).

These are just a few examples based on today's known challenges and opportunities. The space-based research, development and manufacturing facilities will serve as a foundation for continued growth and innovation based on emerging new technologies and application akin to Earth-based systems that have powered the innovations and economic developments in the past century.

Additionally, a key challenge, hence, an opportunity is removal of space debris from low-Earth orbits due to rapid development and commissioning of several constellations of very large number of communication and Earth observing satellites. NASA's space sustainability strategy [4], Europe's introduction of ESA's zero-debris charter [5] and European Union's (EU's) Space Act require a systems engineering approach to enable and achieve the intended goal of space debris removal. For example, designing and developing satellites such that on-orbit robotic can be used to

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recover, re-cycle and re-use their major components for future satellites can reduce the demand for rare minerals and materials used in their fabrication and help in avoiding potential risks of in-space collisions and re-entry of these components that may survive burn-out in Earth atmosphere and reach populated areas of Earth surface. This will achieve the goals of human safety, avoiding the space collision and realizing the economic benefits from re-use of the systems components in an integrated manner.

The vision of the future space economy is not just limited to low Earth orbit (LEO). Government space agencies around the world, notably US, China, European Union, and others have also set their eyes on the Moon and Mars as future destinations and potential economic opportunities that they offer. As we currently move out from Earth's orbit to cislunar space, it is primarily governments and space agencies that provide the bulk of investments. The Artemis Accord signed by 61 countries (as of 1/26/2026), is a manifest of global interest in cooperation to expand terrestrial economy to the Moon and beyond. There is a global fever among entrepreneurs and investors to get into the space market. As a result, for the first time in history a sizeable amount of capital is entering the market. This is similar to the "dotcom" era[3] or even going further back to the gold rush era as entities with investors' backing are rapidly lining up to develop and build the systems and infrastructure that are required to have a permanent presence for mining of resources from the Moon or nearby asteroids. Innovative technologies that will be developed for such purposes will undoubtedly inspire their use and application on Earth in service of humanity, akin to what has occurred since the dawn of space exploration (e.g., telecommunication, navigation, telemedicine, etc.).

While these activities are impactful in kickstarting the space economy beyond Earth's orbit, it is important to note that there is no central coordination effort for developing standards and protocols for development, operation and recycling and re-use of future systems either in LEO or beyond (we will discuss models for central coordination role in section V). Common standards and protocols for 1) modularity, 2) standard interfaces, 3) interoperability, 4) maintainability, and 5) resource generation that are adopted and implemented are required for both hardware and software among developers and operators of future systems in Earth orbit and Lunar outpost. Lack of such standards and protocols will inhibit timely progress in developing and realizing the full potential of the space economy. In the next section, we describe in more detail these five elements that serve as the essential and interdisciplinary pillars required to build a thriving, resilient and sustainable space economy.

III. Elements of the Strategy

Growing the space economy from LEO and GEO to other vantage points, the Moon, Mars and beyond faces great challenges and opportunities. One of the top challenges is lack of a long-term coordinated strategy among government, space industry, and private investors. The current state of space economy can be characterized as linear. Linear space economy refers to a "take-make-dispose" approach. A more sustainable and resilient circular approach incorporates reuse, repair, and recycle techniques to cut demand for materials, especially rare minerals, and lower the life cycle costs. Ultimately a regenerative space economy couples a circular approach with resource generation in orbit or other planetary bodies, designed to become less dependent on Earth and eventually becoming self-sufficient, paving the path to a sustainable and permanent presence in space.

We propose that this strategy to grow the space economy efficiently is based on five interdisciplinary pillars: 1) Modularity, 2) Interoperability, 3) Standardization 4) Maintainability, and 5) Resource Generation. The first three are the foundation of initial and essential elements for growth in space economy. Space systems modularity, interoperability, and standardization enable a "plug-and-play" approach that is flexible, reusable, and ultimately more affordable allowing subsystems, payloads, and even the whole system (e.g. satellites) to be rapidly assembled, upgraded, repaired, or replaced without the need for new design. These three pillars will significantly lower non-recurring engineering (NRE) and production costs which is key to high return on investment (ROI) for both government and industry. This approach is similar to the revolution in the shipping industry in the 1960s when the creation of modular, standardized shipping containers/boxes coupled with wide adoption across the industry had sweeping economic consequences. Adopting the standardized approach made it possible for almost any container to travel seamlessly on any truck, train, or ship and revolutionized the shipping industry. Similarly, industry adoption of common space systems modularity, interoperability, and standardization can revolutionize the space market leading to rapid growth of the space economy. Another example is the space telecommunication industry where reusable

[3] It is important to note that not all dotcom entrepreneurs succeeded. A surge in investor capital isn't necessary an indication of future success in the future.

rockets, ridesharing for launches coupled with miniaturized and standardized satellites have significantly lowered the costs associated with providing reliable telecom services by bespoke satellites from the polar and geosynchronous orbits. Specifically, the rocket reusability and satellite miniaturization and standardization (allowing production at scale) have led to the impressive development and growth of space-based telecommunication industry during the past several decades. In the 1960s, there were primarily 1 to 3 major companies dominating the market with less than 10 operational satellites. Today, there are over 10,000 active telecommunication satellites with majority of them operating from LEO in mega constellations.

The fourth pillar, space systems maintainability, is needed to grow the circular space economy. To be affordable and provide better return on investment (ROI), space systems need to be designed such that they are maintainable. Maintainability encompasses repair, reuse, and potentially any necessary upgrades for better functionality. Maintainability is crucial as we leave the LEO environment and enter cislunar space and beyond since the cost of replacement and resupply coupled with extended times associated with refurbishment from Earth makes less economic sense. In-space assembly, robotic repair and refurbishment, and possibly retrieval for reuse provide significant ROI and are crucial to growing the circular space economy.

The last pillar, ability to generate resources, ultimately renders a regenerative space economy and is crucial especially for expeditions beyond LEO to the Moon, Mars, and beyond. As distance from Earth grows, Earth - independence in operation and servicing, including timely repairs and/or rebuild becomes a crucial factor in achieving permanence and sustainability in space.

Growth in the space economy either in Earth's orbit or cislunar space is directly a function of a) growth in demand of products and services, b) profitability of producing the products and services. There is no question that demand in space products and services (e.g. telecom, broadband, launch services, in-space manufacturing, rare Earth resources, etc.) are on the rise. The question is how profitable are providing the products and services that will enable sustainable growth. As we have observed, telecom and broadband services are experiencing the greatest growth year to year and have proven to be profitable so far. It is really the niche space products and services that are not technologically mature yet and have not proven to be profitable. In addition to a sustainable demand, profitability entails a maturity in R&D and established infrastructure to bring down the cost of non-recurring engineering (NRE). In the following sections, we present the five interdisciplinary pillars (modularity, standardization, interoperability, maintainability, resource generation) that need to be technologically mastered and integrated into the infrastructure for a vibrant growing space economy. We define and expand on each of these below.

A. Modularity

Modularity in space systems involves designs that use standardized components. It uses "plug-and-play" interfaces for subsystems such as payload, power, communication, etc. enabling fast assembly and ease of servicing in orbit. The great advantage of a modular framework over that of a one-off design is that components can be designed independently of each other. For example, payloads can be designed independently from buses according to a set of agreed upon standards, in advance. In addition to enabling seamless manufacturing operations where design of one component is not holding other components' designs hostage, it allows flexibility for choosing a host satellite bus or launch vehicle based on availability, significantly improving flexibility in procurement and launch timeframe. This framework provides a major cost reduction tool by allowing mass production, and reducing non-recurring engineering (NRE) costs, eventually leading to economies of scale.

One of the great benefits of having such modular space systems in orbit is that satellites can be repaired or upgraded with new technology, and their life span can be extended instead of developing and launching new satellites. This approach enables "affordability" in the space economy and will lead to growth, if adopted by industry. For example, in the context of commercial space stations hosting in-space manufacturing, modular design of lab spaces with standard interfaces allows seamless plug-and-play of any type of experiment aboard the commercial space station opening the possibilities for a variety of industries and payloads for manufacturing in space.

There are many levels of modularity such as at the component, subsystem or the entire system level. Modular, Adaptive, Reconfigurable System (MARS) technologies (both hardware and software) facilitate the modular approach. NASA has been at the forefront of pushing these technologies for the past decades [7]. Factoring the optimum level of modularity into space architectures in advance will improve sustainability and cost-effectiveness of individual missions. Coordinated industry adoption in advance is the key to the success of this approach moving

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forward. In section IV we discuss in more detail how this approach revolutionized the marine commerce and shipping industry, major pillars of today's global commerce and supply-chain.

B. Standardization

Standardization principles attempt to establish a set of requirements and interfaces for efficient design, development and operation of space systems. A prominent example is the International Docking System Standards (IDSS) [8] led by NASA, ESA, and other nations that enable joint operations for the International Space Station (ISS). IDSS was developed to aid on-orbit crew rescue and joint operations between spacecrafts built by different nations. With the Artemis initiative, it is expected that new vehicle interface standards will be required to support the infrastructure and campaigns for human exploration of Moon and Mars, including surface mobility requirements standards and those for commercial LEO destinations (CLD).

Standardization is another pillar for cost reduction by minimizing the need for unique, mission-specific engineering and is crucially important for ensuring safety and reliability of multi-spacecraft and multi-platform operations. This pillar also contributes to realizing the full potential of future space systems through scalability, avoiding long time and high costs of developing unique capabilities for each system, and providing flexibility for interface and integration of sub-systems and full systems developed by different partners.

C. Interoperability

Interoperability is achieved when diverse space systems regardless of who manufactures and operates them can connect through standardized interfaces and seamlessly perform a variety of functions such as rendezvous and docking as well as communicate and share resources such as power and data. For example, key focus areas for enabling interoperability between robotic and human exploration systems include communication protocols, positioning, navigation and timing (PNT), power, avionics, rendezvous and docking, environmental control and life support systems (ECLSS), and software. Interoperability is essential for seamless integration and operation of systems by multi-sector partnerships (i.e., bi-lateral and multi-lateral cooperations, public-private partnerships), improving safety and reliability, and benefiting from innovations from multiple organization and reducing overall costs through cost-sharing.

Achieving interoperability hinges on industry and government coordination in standards development and effective adoption and implementation to allow a seamless "plug-and-play" in design, development and operation and in sharing of the resulting data and information for diverse applications and uses by partners. While interoperability improves overall mission capability and safety and lowers costs, there are substantial challenges associated with it that requires considering a balance between standardization and data/information sharing with due attention to proprietary constraints. A recent example of this challenge was when NASA astronauts, Sunita Williams and Barry "Butch" Wilmore, who visited the ISS in 2024 via the Boeing Starliner capsule, got "stranded" for several months on ISS when it wasn't safe for them to take a ride back to Earth on the same Starliner capsule due to thruster issues. Each company's spacesuit was designed specifically according to its capsule's design, operation and safety constraints. For example, key differences between the Boeing Starliner and the SpaceX Dragon spacesuits included umbilical connector mismatch for life support systems, and communication ports. Because of this lack of interoperability, astronauts traveling on different capsules must use specific spacesuit that is compatible with the respective capsule. As a result, NASA had to arrange for SpaceX spacesuits to be available to astronauts for them to fly back to Earth on SpaceX Dragon capsule, prolonging their return schedule. Currently spacesuits developed by each company is protected by intellectual property and therefore under the current NASA contracting mechanism, spacesuit technologies developed by different vendors aren't necessarily interoperable. This example illustrates one impediment and the importance of interoperable design standards needed for seamless operations, especially under emergency conditions, at scale and for more cost-effective solutions.

D. Maintainability

To promote space sustainability and lower overall costs, it is crucial to design space systems with maintainability in mind. Maintainability allows systems to be restored to operational status, increasing their lifetime through upgrades with new technologies, as well as ensuring operational safety and continuity. This involves designing systems with accessibility and easy component interchange in mind, as well as incorporating maintenance and repair strategies in the design process. Maintainability in the harsh space environments often requires modular design with easy access to exchange faulty components. NASA has documented maintainability program requirements for space systems to provide common general requirements to ensure maintainability characteristics through the systems engineering process [9]. These requirements have been periodically updated and incorporated in NASA Standards Documents [10] for the purpose of avoiding past design and engineering shortcomings and benefiting from the lessons learned and experience gained from operation of a variety of space systems.

Recently, commercial startups such as ThinkOrbital have been working to develop tools for in-space repair. For example, they plan to demonstrate operation of a robotic arm in space equipped with X-ray imaging capability for diagnosis purposes and a welder gun that could be used to repair components or sub-systems [11]. As characterized by the company, this could be the first step toward the construction of an orbital “toolkit” for building and repairing spacecrafts. NASA’s On-orbit Servicing, Assembly, and Manufacturing 1 (OSAM-1) mission is another example providing robotic in-space servicing capabilities (canceled by NASA in 2024 due to cost overrun). If the commercial sector can demonstrate feasibility of such tools and capabilities at current market-based acceptable costs, it will be a game-changer in terms of paving the path for a circular space economy.

Maintainability of satellites in Earth’s orbit not only makes economic sense, once the tools and infrastructure are in place, but also is crucial to space sustainability effort. There are currently over 12000 spacecrafts in orbit that are operated by 70 nations, and this number is exponentially growing with the introduction of mega-constellations of communication and Earth observing satellites. Unfortunately, the Earth’s orbit is being crowded by mega constellations of satellites with no advanced planning or enforceable regulation world-wide for methodical and safe deorbiting, once they have reached their useful life span. This problem is further exacerbated as evidenced by the rapid pace of launches of constellations, and projected demand for future launches. The accumulation of defunct satellites over time will create a space situational awareness crisis if it isn’t dealt with thoughtfully as soon as possible. Defunct satellites should be removed from orbit to mitigate the risk of creating additional space debris due to potential collisions as these satellites are no longer maneuverable. At the same time, with proper on-orbit recovery and re-use capabilities they can be mined for valuable resources such as rare Earth minerals and other useful components such as solar-arrays, communication systems, etc.

E. Resource Generation

Resource generation in space, either in orbit or on other planetary bodies is the next required step for successful execution of the proposed strategy. In Earths’ orbit, a few startups have already started on this path. Starfish and ThinkOrbital are just two of the emerging companies that are pursuing active space debris removal in addition to potential in-space storage and manufacturing. Another company, Interlune is planning to harvest precious resources such as Helium-3 from the Moon and bring it back to Earth to supply rapidly growing industries such as quantum computing and medical imaging.

Resource generation on other planetary bodies such as Moon and Mars commonly referred to as In-Situ Resource Utilization (ISRU) is an absolute necessity for sustainable presence on other planetary bodies since it is too expensive to bring resources from Earth for long-term and sustainable presence. The investments for R&D efforts and ultimately developing and operating the ISRU infrastructure are crucial to the goal of sustainable presence on other planets and long-duration space travel. The highest priority commodity is power and propulsion which can be generated through a variety of technologies, most notably through nuclear reactors, ion propulsion and solar energy harvesting techniques. NASA is in the process of funding the R&D required for developing the power infrastructure on the surface of the Moon through multiple awards to industry for both nuclear and solar powered systems. Having sufficient power to operate on the surface of the Moon is the prerequisite for all other resource generations, such as harvesting the regolith for water, oxygen, hydrogen, and valuable minerals for wide applications such as developing fuel or building infrastructure such as landing pads and habitats.

IV. Comparative Case Studies by Other Industries

In this section, we describe a comparison with two other industries that achieved phenomenal growth in the last decades, the marine commerce and the space telecommunication industries, respectively. In both cases, the tipping point was reached when standardization and interoperability were widely adopted by the industries, resulting in exponential growth and production at scale, and benefited all involved nations and industries.

Marine Commerce Case

The marine commerce and transportation industry is a classic case of how standardization, interoperability, and modularity were employed to drive a revolution in global shipping and supply chain industry, making operations more efficient, less costly, and at unprecedented speed. The details are summarized in the book, “The Box: How the shipping container made the world smaller and the world economy bigger” [12]. The creation of modular, standardized shipping boxes, coupled with wide industry adoption had sweeping economic consequences. Adoption of these capabilities made it possible for the standardized container to travel on any truck, train, or ship (achieving the integrated power of modularity, interoperability, standardization) and revolutionized the industry.

The journey to get there, however, was not a smooth one. From the late 1950s to early 1960s, the “container” was a collection of competing proprietary systems. Companies competed for their designs to become the global standard. It took decades of international and technical negotiations known as the “Standardization Wars” to agree on the standards that finally led to the universal International Organization for Standardization (ISO) standards. The top two companies had completely incompatible designs.[4] To achieve a global standard, the industry had to agree on dimensions, corner fittings (which enabled a crane to grab the container), and strength rating (how many boxes can be stacked on top of each other without crushing the bottom ones). Progress was finally made when Malcom McLean agreed to release his patents on corner fittings royalty-free, essentially “open sourcing” the technology to finalize the standards in the mid 1960s.

The mid 1960s saw the first introduction of the international container services, although initially shipping lines suffered from massive capital costs with the introduction of the new ships and equipment. It was during the Vietnam War, when Malcom McLean convinced the U.S. military to use containers. At the time, the U.S. military was facing a “logistical nightmare” in Vietnam [12]. Malcom McLean proposed an overhaul of the shipping scheme by building the infrastructure (docks, supplying cranes and managing the trucking) and ensuring that ships would be doubly used not coming back empty from Vietnam but stop by Japan to pick up consumer products for the American market upon their return. The success of the overhaul in massive military logistics operation demonstrating speed, security (sealed containers immune to theft), and globalization of trade proved the system could work globally and at scale. This tectonic shift in standardization combined with modularity and interoperability allowed the shipping industry to scale globally and render enormous growth in the world economy.

Space Telecommunication Case

The space telecommunication industry has grown exponentially in the previous decades and has almost entirely transitioned from government-led to commercial-led. This phenomenal growth has been the result of many factors but most notably due to reduced launch costs because of reusable hardware (maintainability factor) and increased launch frequency with rideshare opportunities (affordability and ease of access factors) as standardization and interoperability played a major role in at-scale production and operation of the systems.

Growth has also been fueled by a shift from large, complex, expensive satellites in GEO to mega constellations of smaller satellites in LEO which provides low-latency broadband suitable for consumer use. Advancement of connectivity technologies such as Direct-to-Device (D2D) has provided seamless integration of satellite services directly into smartphones and tablets, providing sustainable and growing demand by consumers.

The combination of these successes has led to huge consumer demand which in turn has driven massive private equity investments in space-based broadband communication, providing most of the growth in the space economy in this sector. Indeed, the revenue from consumer demand for satellite broadband from 2022 to 2023 increased by 40%. This growth is largely attributed to the SmallSat constellation proliferation and most satellites launched in recent years are for LEO broadband applications [13]. This chapter in space-based communications and its future trajectory is still in early stages as greater number of nations and companies are introducing new constellations. To avoid unintended consequences such as space-debris and collision hazards, it is even more imperative that our proposed strategy be adopted and implemented.

[4] Sea-Land used 35-foot containers while Matson Navigation used 24-foot containers. Other companies experimented with 8, 10, and 17-foot designs. Because the containers were of different sizes, they could not fit on standard rail cars or be lifted by different cranes. This lack of interoperability meant the system could only work if one stayed within one company’s network.

V. Strategy Implementation

The integrated approach outlined in our proposed strategy is designed to result in economic benefits by lowering the costs and promoting greater economic growth in the long run. Besides economic growth, aspects of this approach such as maintainability (in-space servicing) and resource generation (e.g. via orbital debris removal and reuse of resources) avoid adverse consequences of orbital congestion, accidental collisions, and promote sustainability of the space environment for generations to come. Lack of action to foster and embrace space sustainability and a circular space economy (reuse, repair, recycle approach) due to perceived increased costs in the short term will result in hidden negative costs in the long run, as experienced in marine commerce and transportation case. To offset the initial increased costs of implementing a space sustainability framework which will foster greater economic growth, providing economic incentives shored up with guided policy and focused regulation are essential ingredients for success.

A critical question pertaining to implementing this strategy is whether the activities should remain organic allowing trends to emerge, or should these efforts be carefully coordinated, monitored, and course corrected by self-organization of the parties? If choosing the coordinated approach, how should the coordination and integration be achieved? Should the overall integration and coordination be guided by the governments, commercial industry, or a consortium of both sectors? History has proven that coalition of like-minded and self-organized entities are more sustainable and successful because of their vested interest in success and benefits for all parties involved.

In the following section we offer some ideas on how to implement this strategy. These ideas are intended to stimulate innovative thinking and approaches focused on: mechanisms for a coordinated approach by parties, developing technologies needed to enable this approach, acquisition strategies as well as thoughts on policies and regulation, and very importantly the need for workforce development that is foundational.

A. Coordination and Adoption by Industry

It goes without saying that the strategy and approach outlined won't work unless the five pillars are adopted and implemented in a coordinated manner by the stakeholders of space economy (i.e., government, industry, academia and investors). We propose that the integrated strategy approach outlined in this paper to be adopted for a coordinated implementation by a consortium of aerospace industries that have a common goal of growing the space economy. There are already some of these consortia in place such as CONFERS (the global Consortium for Execution of Rendezvous and Service Operations), COSMIC (the Consortium for Space Mobility and ISAM Capabilities), and many others who continue to serve as a catalyst for the vision of growing the space economy. Collaboration and coordination are key to building the coalition for a vibrant future space economy. This integrated and coordinated approach is needed for in Earth orbit (for in-space servicing, assembly, manufacturing, debris removal, and resource recycling) as well as in cislunar space and beyond. In cislunar space, while efforts such as the Artemis Accord are laudable, a lack of coordination for planning, interoperability and standardization across the space ecosystem is missing which will hamper timely progress for building lunar infrastructure and a vibrant lunar economy, at scale and fast pace.

We propose that the global consortium of space industries should lead this coordination effort with help from global space agencies and governments who can foster and enable this approach with effective policies, thoughtful acquisition strategies, incentivized regulation, and public-private partnership mechanisms. Such global consortium should first develop a governance model with membership rules, followed by development and adoption of standards, enforcement mechanisms, compliance monitoring, and dispute resolution.

B. Research & Development (R&D)

The five pillars outlined here stand on the foundation of cutting-edge research and technology development for space systems that enable modularity, standardization, interoperability, maintainability, and resource generation and utilization. There is inherent high risk associated with this type of R&D and the question is who should bear such risks? We suggest that investments for essential high-risk R&D should continue to be spearheaded by governments and space agencies by providing initial seed funds for low technology readiness level (TRL) projects. The role of Governments in this regard should be viewed as venture capitalists for providing the seed fund and be allowed to take a share of the profit if the effort is successful for the intended purpose. Such profits can be the seed funding for investment in future high-risk R&D projects. Other approaches may include government-industry cost sharing through mechanisms such as space act agreements and in-kind leveraging of resources, to name just a few.

Here is another opportunity for creative thinking and partnerships with the shared purpose of advancing and growing space economy at the national and global level. Space agencies such as NASA (who has been leading space missions since 1950s) have the technical expertise to provide technical advice to the commercial space sector while funding the development of technologies needed for its continued advancement and growth. The role of NASA funding the development of the commercial crew program (CCP) while providing technical advice is an example of a successful public-private partnership and should be a model of how to help commercial space companies gain valuable technical expertise to succeed in the risky space business. We are truly inspired by the diversity of space enterprises emerging at a rapid pace. Without a coordinated and integrated strategy and approach the full potential of such a vibrant growth may not be realized in a timely and efficient manner.

C. Policy & Acquisition Strategy

As government policy is shifting toward “commercial first” mantra, the role of NASA is shifting from “doer” to “procurer”, “space architect”, “integrator”, and “enabler”. Therefore, acquisition strategies and associated policies are expected to be in lock step with R&D needs, systems engineering, and the overall integrated architecture should be shifting to enable the growth of the space economy. While it is important that acquisition strategies refrain from being overly prescriptive to hamper innovation, however, they should embrace the perspective that beyond achieving new capabilities through scientific and technological innovations the architecture of space systems should also advance and grow the space economy. An example for illustrating this point is the acquisition strategy for commercial crew transport systems which did not require spacesuits compatibility from SpaceX and Boeing to be interoperable regardless of the commercial space vehicle for transporting astronauts and other potential space travelers. When the Boeing Starliner capsule proved risky for returning astronauts back to Earth from the ISS, the lack of interoperability of the spacesuits contributed to the crew of the Starliner being forced to stay on ISS for several months longer because of this incompatibility of their spacesuits with those required for the SpaceX Dragon (see discussion in Section III-C). In this case, restricting intellectual property (IP) policy confined to separate acquisitions prevented standardization and interoperability of the spacesuits with spacecrafts built by the two companies (see discussion in Section IV on how open sourcing of technology enabled growth of the marine commerce). This issue may continue to persist if not remedied with the upcoming acquisition strategy for commercial LEO destinations (CLDs) where interoperability must be ensured through the acquisition strategy and incentivizing technology sharing (possibly through reforming of intellectual property policies). A better outcome is the willingness of the private sector to spearhead proactively the development and adoption of such standards to provide them with greater degrees of freedom for managing and mitigating risks of future incidents, especially for long duration space travel. Open data sharing across government and commercial space ecosystem can further enable interoperability to succeed. The acquisition strategy may also include innovative means and incentives for vendors to be rewarded for adopting standards and/or sharing information to compensate for their short-term economic objectives.

D. Business Models

As venture and private capital funding for space systems development is growing rapidly, it’s also important to devise overall coordination mechanisms that promote and enable an integrated implementation of the major pillars of the proposed strategy among public and private funders. While there is some organic coordination among these groups, it remains varied and unstructured. To accelerate the growth of the space economy, it is necessary to move beyond informal interactions and establish structured financial engineering and integration (FE&I) processes. In the realm of constructing space systems, we rely on systems engineering and integration (SE&I) to ensure project success. It is now time to apply these same SE&I principles to the creation of business models through FE&I. This approach will enable development of effective business models that seamlessly connect investors, startups, insurers, academia, and other crucial parties within the space ecosystem. Similar to the consortium for adoption of space system standards and interoperability, a consortium of key public and private funding players in space economy should play the role of coordinators akin to a market depot, actively integrating investments and matching them with individual players while emphasizing the need for coordination and integration holistically across all essential pillars for a resilient and agile space economy. To illustrate this, let’s consider a case study for in-space manufacturing in microgravity environment. This applies to a broad range of applications such as manufacturing semiconductors or biotech related products. Funding should be planned and secured end-to-end for all aspects of such projects that includes on Earth and in-space elements from design and development such as launch, in-space logistics to returning manufactured products back to Earth for utilization. Often the process of acquiring funding for each phase is uncorrelated raising a lot of questions and risks for funders and resulting in sub-optimal or unsuccessful implementation due to weakest link affecting the success of entire project. However, if an in-space manufacturing market depot is set up and coordinated in advance by integrating its funding mechanisms and bringing together suppliers with funders and aligning them with engineering and operations aspects, the risks will greatly diminish, and the implementation of entire project will speed up resulting in creation of a vibrant marketplace.

E. Regulations

The aviation industry growth and its regulation is the closest example for how the space economy can grow and be regulated. From the first commercial airline flight in 1914 with only one passenger to the global busy skies of today with well over 100,000 flights per day and millions of passengers, the road to building the airline flight industry of today was packed with regulation to ensure safety of both passengers and those on the ground as well as interoperability of ground equipment with any aircraft. The flight industry not only catered to passengers for leisurely travel but also placed a high premium on safety and security of travelers. Various applications spun from the invention of airplane that benefitted military and commerce. Inevitably space industry supported and embraced regulations that are currently managed by FAA Office of Commercial Space Transportation to ensure launch safety, FCC to regulate satellite communication frequency, and NOAA's Commercial Remote Sensing Regulatory affairs (CRSRA) that issues licenses for commercial remote sensing satellites. Although these entities were established sequentially and their mission and activities were coordinated afterward, it will be most effective to consider how such activities can be established in an integrated manner based on lessons learned and experience gained from the aviation enterprise. Such efforts will be needed not only to promote and ensure safety and seamless operations but also to provide incentives to advance and grow the space economy. A consortium of regulation experts can work closely with the industry consortium to develop policies and regulations needed to ensure safety and growth of a vibrant and sustainable space economy.

F. The Importance of an Agile Workforce for the Growing Space Economy

A well-prepared and agile workforce serves as a fundamental component and key opportunity for establishing and expanding a resilient space economy. The science, technology, engineering, and mathematics (STEM) fields form the backbone of the U.S. economy. More than 73 million Americans are employed in STEM-related professions, representing approximately 34% of the total workforce. Collectively, these professionals contribute over $10 trillion to the nation's gross domestic product each year, accounting for about 40% of the total economic output [14, 15, 16, 17].

Rapid advancements in capabilities and tools are transforming every aspect of the space enterprise, from concept development and project design to program implementation and daily operations. These changes require a workforce that can swiftly learn and apply emerging technologies. Such adaptability is critical for ensuring efficiency and effectiveness across project scheduling, cost management, oversight, and integrated implementation. Technologies including 3D printing, quantum sensing and computing, and AI-enabled capabilities are increasingly vital to the success of the rapidly growing space economy. To maintain a competitive edge domestically and globally, the workforce must be adequately trained and prepared to utilize the current and rapidly emerging technological innovations [14, 15].

Despite the rapid growth in STEM fields, a considerable skills gap persists. Society has not fully anticipated future employment needs across sectors such as space, resulting in an underdeveloped pipeline of high-skill labor. This gap threatens economic growth and innovation. Many STEM professionals aim to advance their careers through further education and stackable credentials; however, shortages of such credentials remain, especially in large metropolitan areas where most space sector reside. The central challenge is to expand the STEM workforce to meet current needs and anticipate future demands. Addressing this issue requires a shift in how STEM careers are perceived by educators, employers, policymakers, parents, and students. It is necessary to look beyond traditional pathways that require four-year or advanced degrees and to lower barriers to entry, such as cost, time commitment, and perceived difficulty in acquiring STEM skills [17].

National and international assessments indicate that career pathways leading to technology fields such as space sector can substantially increase earning potential. Bridging workforce pipeline gaps demands coordinated action from educators, policymakers, and industry leaders. Key strategies include enhancing vocational training, refining credential pathways, and boosting employer involvement in education development. Aligning workforce skills with industry needs is vital for ensuring economic prosperity and solidifying the foundational role of STEM in America's

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future. Flexibility and agility of academic and education organizations to respond in timely manner to such demands is also key to success. For example, some education and academic organizations are revisiting their standard curriculum as they prepare to become more agile in responding to the need for current and future skills. These efforts will support progress in STEM workforce development, help fill gaps that impede innovation and growth in the space economy, create education and training pathways for the future workforce, and expand opportunities for all Americans to enter STEM careers—critical for U.S. leadership in the global space economy. Recognizing the inclusive nature of science and technology and their central role in the American economy, combined with educational, training, and policy initiatives, is essential for ensuring the nation's future prosperity and competitiveness.

VI. Conclusions

We have outlined an integrated strategy focused on advancing and growing the space economy, while also fostering space sustainability for future generations. This strategy is anchored by several key pillars: space systems modularity, standardization, interoperability, maintainability, and resource generation. These pillars should be implemented in a coordinated and integrated manner to enable safe and sustained presence and operations both in Earth's orbit and on other planetary bodies, including through in-situ resource utilization (ISRU). Furthermore, this approach is necessary for mobilizing the required financial resources through public-private partnerships and other innovative mechanisms.

The execution of this integrated strategy requires close coordination among space agencies, the commercial space sector, and governmental bodies. Success relies on the voluntary adoption of the five pillars by the space industry, supported by incentivized acquisition strategies, targeted policies, and robust regulations. Research and technology development form the foundation of the strategy, making it essential for governments and space agencies to provide seed funding for R&D through thoughtful public-private partnerships and other innovative approaches.

The sustainability and evolution of this strategy are contingent upon comprehensive workforce development and retention initiatives. Without cultivating the next generation of space professionals, this strategy cannot be executed or sustained.

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Conflict of Interest

The views and ideas presented by the authors in this paper are intended to facilitate a dialogue and sharing of ideas for advancing and growing the space economy here in the U.S., and globally, without attribution to any organization or entity.

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