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Space Science & Technology Partnership Forum: Value Proposition, Strategic Framework, and Capability Needs for In-Space Assembly

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The Space Science and Technology (S&T) Partnership Forum was established in 2015 to identify synergistic efforts and technologies across the government, with a focus on key pervasive and game-changing technologies across government space agencies in order to more efficiently and effectively manage S&T resources. As principal partners of the interagency S&T Partnership Forum, the U.S. Air Force (USAF), the National Aeronautics and Space Administration (NASA), and the National Reconnaissance Office (NRO) identified and prioritized several S&T collaboration topic areas. Autonomous and semi-autonomous in-space assembly (iSA) is the focus of the topic area that NASA, under the direction of the Office of Chief Technologist, is currently coordinating among the S&T principal partners and affiliate partners, such as the Defense Advanced Research Projects Agency (DARPA) and the U.S. Naval Research Laboratory (NRL). The S&T iSA facilitation and analysis team, led by NASA, collected data from the participating agencies on their current developments, activities, and needs in the area of in-space assembly. This paper provides an overview of the S&T iSA facilitation and analysis team's efforts in establishing the value proposition and strategic framework for interagency collaboration in iSA within the partnership as a foundation to deliver value and achieve iSA topic objectives across government space agencies. Further, this paper describes the early products of these efforts in the definition of the iSA capabilities, design drivers, and stakeholder goals to facilitate dialogue within the partnership and the larger community.

I. Introduction

The various space agencies of the U.S. federal government have distinctly different visions for future operational space systems, as befits their distinct missions, but they are all seeking to improve mission performance, reduce mission costs, and incorporate technology advances more rapidly. These common needs, combined with significant launch cost reduction for smaller commercial vehicles and advances in the automation and robotics technology base, have led the agencies independently to an interest in developing the technology for assembling spacecraft in space.

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The technological foundations for these capabilities are largely independent of the operational mission, allowing the federal agencies to consider how they could combine their efforts to make better use of the taxpayers' funding. Looking across the space agencies' current in-space assembly (iSA) technology development portfolios provides an opportunity to identify synergies, redundancies, gaps, and risk-reducing parallel paths so that the necessary and sufficient set of capabilities can be deliberately developed. Where appropriate, technologies could be developed with common features, interfaces, and performance metrics to allow those developed by one agency to be readily adopted and/or adapted by the others.

II. In-Space Assembly

From the beginning of the space program, spacecraft have been built, integrated, and tested on the ground before being launched, then relegated to junk when their mission life ended. As spaceflight moves into its second half-century, this traditional approach has reached an asymptote at which the next increments of performance become impossible or prohibitively expensive. This asymptote comes at exactly the time when several advances in un-crewed spaceflight capabilities coalesce to make it possible to assemble major structural components in space, to service and upgrade spacecraft there, and ultimately to manufacture components in space. The new paradigm could initiate a new performance curve, inviting innovations that would make established uses of space far less expensive and wholly new uses feasible.

The traditional way of building spacecraft leads to vicious cycles of spiraling costs. Because launch costs dominate mission costs, payloads were built to high standards of reliability to ensure mission success, which increased payload development costs. The higher-cost payloads motivated higher-reliability launch vehicles, which increased launch costs even more. The drive for payload reliability also motivated system integration before launch which, as space operators reached for the next increments of performance with larger systems, mandated larger and heavier-lift launch systems. This traditional approach has driven the most futuristic spaceflight needs, like a human mission of Mars, to develop phenomenally expensive heavy lift to solutions that may still have inadequate mass and dimensional constraints.

Another consequence of theses cycles of spiraling costs due to the traditional way of building spacecraft is technology obsolescence. As previously mentioned, the cycle drives the need for payload system integration before launch, which can lead to fully-formed, payload technologies that are 5 to 10 years old at launch with consideration of the timeline for the technology development. Given a typical on-orbit operational mission lifetime of 15 years for the payload, the payload technology is 25+ years old at the end of the mission [1].

The new, low-cost commercial launch systems have the potential to break the spiral for payloads that can meet their constraints. For large structures to take advantage of them, they must be assembled in space. Although the International Space Station (ISS) served as a proof of concept for assembling large, pre-integrated, modular structures on orbit, it depended on the capabilities of the Space Shuttle, required an enormous amount of human labor on orbit, and the payloads were designed for the launch vehicle ascent environment loads, which demanded significant additional mass, called parasitic mass. This mass incurred higher launch costs and had no function after launch. This approach also drove the need for large and expensive ground facilities to handle assembly, integration, and test (AI&T).

Since then, advances in automation and robotics have opened the possibility of building up large structures on orbit beginning with relatively simple components, significantly expanding the design options for spacecraft, such as to enable large persistent assets to be assembled and routinely upgraded to achieve unprecedented aperture size and technology refresh. By relieving the launch fairing and mass constraints associated with launching large, monolithic, pre-integrated payloads, iSA would allow better designs and extended configurations without the system complexity and parasitic mass of on-orbit deployment. Structures assembled in space may be designed for operational loads, instead of launch loads, and are likely to be much lighter. Payloads may be designed to be modular, with the option to launch each module separately on smaller, more cost-effective launch systems vehicles. If launched together on a larger vehicle, the payloads also may be designed to package efficiently in smaller envelopes. Such payloads may be assembled and verified in space, the actual operational environment.

The modularity achieved through iSA has many advantages, including improvements to performance, longevity, cost, and risk. For example, a modular payload and spacecraft system design may allow designers to incorporate features that allow extensible spacecraft. A large radio frequency or optical aperture, or a large power generation system such as solar array or concentrator, may be constructed in a way that accommodates additional modules. This accommodation would achieve performance beyond that of monolithic or deployed designs used for ISS, which have limited extensibility and rely heavily on human operators. The technology base needed to assemble structures should also enable the repair or upgrade of satellites that are already deployed, extending their life (persistence) or improving their performance, thus reducing the need for new development and launch costs. The Hubble Space Telescope (HST) is perhaps the best exemplar of this paradigm change. The HST is far more capable today than when it was launched over 25 years ago, due to technology upgrade and installation of orbital replacement units (ORUs).

Additionally, incremental buildup distributes the cost across time and facilitates cost sharing by multiple programs and possibly multiple government agencies. A 20-meter evolvable telescope with the primary structure assembled in space is estimated to cost half that of a telescope whose primary structure is assembled on the ground, a savings of nearly $13 billion [2]. Modularity may also reduce cost by enabling launches of smaller, modular components on smaller, lower cost commercial vehicles. In addition, this may likely enhance competition among all U.S. launch providers. In turn, these lower costs reduce system and mission risk. Moreover, a failure on a small launch vehicle for a very large system would destroy only a module, instead of the entire spacecraft, making replacement less expensive.

Space-faring agencies of the U.S. government, along with commercial space companies, recognize the exciting potential for this new paradigm in spacecraft assembly and servicing. Developing the technology and systems to bring such a capability to operational readiness will benefit from broad cooperation towards a shared goal. Space robotics programs at government agencies are already addressing challenges in validating on-orbit robotic operations with missions, including Restore-L and Robotic Servicing of Geosynchronous Satellites (RSGS), and other projects [1]. These activities provide significant momentum which can be used in demonstrating the capabilities of iSA.

III. The Space Science and Technology Partnership Forum

The Space Science and Technology (S&T) Partnership Forum was established in 2015 to identify synergistic efforts and technologies across the government, with a focus on key pervasive and game-changing technologies across government space agencies in order to more efficiently and effectively manage S&T resources [3]. The S&T Partnership Forum is chaired by the Air Force Space Command (AFSPC) Chief Scientist, and has three principal agencies: the U.S. Air Force (USAF), the National Aeronautics and Space Administration (NASA), and the National Reconnaissance Office (NRO). Additionally, the Forum has participation from the Office of the Secretary of Defense Research and Engineering, Office of the Assistant Secretary of the Air Force for Acquisition (Science, Technology and Engineering) (SAF/AQR), the Defense Advanced Research Projects Agency (DARPA), the National Oceanic and Atmospheric Administration (NOAA), the U.S. Army's Space and Missiles Defense Center (SMDC), the Air Force Research Laboratory (AFRL), and the U.S. Naval Research Laboratory (NRL). Since the Forum membership consists of agency and organization chief scientists and technology officers, the Forum naturally provides a multiagency voice on government S&T to advise senior leaders on synergies, collaborations, and the state of the art for space technologies.

The S&T Partnership Forum has a near term goal of actively working to cross-walk USAF-NASA-NRO road maps to identify opportunities for synergies and collaboration in technology investments. Additionally, the Forum will develop a strategy for a joint roadmap that focuses on mutually beneficial long term goals. The S&T Partnership Forum is accomplishing this through personnel exchange, technology evaluation collaborations, and multiple Technical Interchange Meetings (TIMs) [3].

As principal partners of the S&T Partnership Forum, the U.S. Air Force (USAF), the National Aeronautics and Space Administration (NASA), and the National Reconnaissance Office (NRO) identified and prioritized several S&T collaboration topic areas, including small satellite technology, big data analytics, autonomous or semi-autonomous in-space assembly (iSA), and cybersecurity [3,4]. As the pilot to cross-walk NASA-USAF roadmaps, the S&T Partnership Forum chose the small satellite technology area.

For the S&T collaboration topic area of iSA, NASA, under the direction of the Office of Chief Technologist, is currently engaging and coordinating with the other principal partners as well as with affiliate partners of the S&T Partnership Forum, including DARPA and NRL. The S&T Partnership Forum serves to coordinate and facilitate partner dialog, collect data and perform data analysis, and assemble data products into recommendations for partnerships to be executed within the S&T community at the program and project levels within the partnering agencies. The S&T iSA facilitation and analysis team, led by NASA, worked to establish a value proposition and strategic framework for interagency collaboration in iSA within the partnership as a foundation to deliver value and achieve iSA topic objectives. The early products of these efforts are the definition of iSA capabilities, design drivers, and stakeholder goals to facilitate dialogue within the partnership and the larger community. The information to accomplish these study objectives was collected from and/or validated by partnership representatives with specific knowledge of their agency's mission needs, program plans, and technology investments.

Government agencies and U.S. commercial space companies have individually been developing and investing in this new paradigm of spacecraft assembly and servicing. These pursuits have been separate because government agencies and commercial companies have different priorities, with commercial companies largely focused on in-space servicing (iSS). It is clear, however, that government and commercial efforts to mature iSA and iSS technology would benefit from cooperation, strengthening a shared knowledge base. A common core of high-leverage technologies in structural joining, utility connection, and metrology enabled by advances in autonomous robotic systems exists. This common core should guide a shared path towards robust and flexible capabilities for a wide range of U.S. commercial and government applications requiring iSA and iSS [1, 2].

To begin strengthening this cooperation and prompt the development of iSA capabilities, a S&T Partnership Forum TIM occurred in February 2017. This meeting identified cross-cutting applications of iSA and the benefits of developing a robust iSA capability for future space assets. A second TIM also occurred in August 2017, in which the participants identified the list of iSA capabilities relevant to the various agencies and assessed how well the capabilities aligned with the stakeholder's goals and design drivers for iSA.

IV. Value Proposition

An explicit value proposition is the foundation of an effective strategic plan to realize the benefits of iSA to the S&T Partnership Forum. The value is defined by how the S&T Partnership Forum stakeholders find worth, utility, benefit, or reward for their respective contributions to the enterprise, and the enterprise value proposition process is shown in Figure 1.

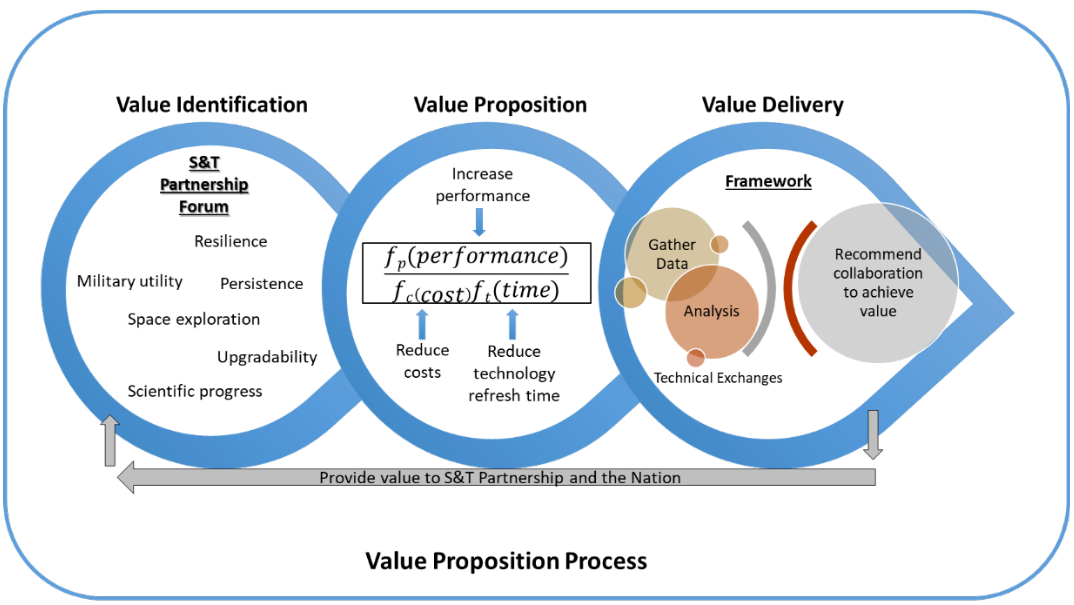

Fig. 1 Value proposition process.

As shown in the iSA value proposition process in Figure 1, the value is determined in three primary steps:

1. The first step is to identify the stakeholders (S&T Partnership Forum and the Nation) and describe their value expectations. These values serve as an input to the next step and are defined below.

- Resilience: Resilience is the level of invulnerability of a system in the presence of stress or in the event of an adversarial attack. Resilient systems have the ability to quickly restore their original capability after being disturbed. Highly resilient systems maintain their capability under extreme environmental conditions and under much larger adversarial actions.
- Military utility: Military utility describes the capability of the space system to achieve military objectives through operational effectiveness, suitability, availability, interoperability and affordability. One key utility need is space situational awareness. Space situational awareness includes both full spatial awareness and full temporal awareness. Full spatial awareness includes all elements and events both within the atmosphere and in Earth orbit. Full temporal awareness includes elements and events continuously and in real-time, including estimation and prediction of future situations.
- Upgradability: Upgradability is the ability to improve performance and/or effectiveness of a system architecture by replacing sub-systems with newer and better capabilities. Upgradability allows current space assets to improve both mission capability and resilience with time.
- Scientific progress: The stakeholders seek to advance science, technology, aeronautics and space exploration to enhance aerospace knowledge, education, innovation, economic vitality and stewardship of Earth. Improved robustness, mobility, and longevity of robotic systems also enhance science performance.
- Space exploration: The stakeholders pursue their missions through critical research and technology demonstrations, promotion of a robust U.S. commercial space industry and space systems and robotic exploration of Earth from orbit and of the cosmos beyond.
- Persistence: Persistence is the continued or prolonged existence of a space systems and its required capabilities and operations, even in the presence of difficulty or adversarial opposition. Key contributors to enabling persistent space assets are their abilities to be upgradeable and highly resilient.

2. The second step is the development of a robust value proposition to meet stakeholder expectations. Equation (1), also shown in Figure 1, gives a general statement for the value proposition. The calculation of the iSA enterprise value (i.e., the value of iSA to the S&T Partnership Forum collectively as opposed to the value individually for each partnering agency) involves contributions of cost ($f_c(cost)$), time ($f_t(time)$), and performance ($f_p(performance)$).

$$iSA\ Enterprise\ Value = \frac{f_p(performance)}{f_c(cost) \cdot f_t(time)} \qquad (1)$$

- Performance: The values identified by the stakeholders of the S&T Partnership Forum inform the performance contribution to the iSA enterprise value.
- Cost: The cost contribution to the iSA enterprise value reflects the costs to develop, launch, and operate space systems. In addition, cost also can be affected by approaches that allow for incremental funding rather than requiring a single large payment before the system produces any utility. This pay-as-you-go approach minimizes the risks and burdens of early commitments of funds. This approach also spreads out the cost burden over the life of the project or individual capability improvements. The S&T Partnership arrangement would further reduce cost by sharing facilities, eliminating redundant developments, and collaborating on similar iSA capability needs.
- Time: The time contribution to the iSA enterprise value is determined by the time between the availability of a new technology and its use in orbit. Obsolescence describes the loss of utility of capabilities relative to the performance that the latest technology can provide. The current, standard method of fielding space systems makes them obsolete almost from the time they begin operation. The five- to ten-year development and deployment times make avoiding obsolescence increasingly difficult. The next generation of iSA-enabled space systems should reduce the time between when a new capability or new technology becomes available and when it achieves use on orbit.

3. The third and final step involves determining the options for collaboration to deliver the value, or to deliver on the promise of the expected technical and programmatic performance. Collaboration enables the government to achieve an effective and efficient path toward delivering value, and categories for collaboration may include knowledge, resources and technology, and systems.

Partnership between government agencies with common technological needs for iSA offers efficiencies through cost sharing, elimination of duplication, reduction in overhead costs, pooling of resources, and the exchange of expertise and knowledge. The S&T Partnership Forum can proceed towards these benefits by following the strategic framework outlined in the next section.

V. Strategic Framework

After completing the value proposition process, the S&T Partnership Forum developed a strategic framework for interagency collaboration, a plan to enable the government to achieve an effective and efficient path toward delivering value. The strategic framework for the S&T Partnership Forum's engagement in the iSA collaboration topic area is shown in Figure 2. This framework guides the execution of activities within the partnership to explore cooperation on iSA. As seen in Figure 2, the framework consists of three phases. Each phase provides a measurable return on investment (ROI) aligned with the goals. The phases also progressively build understanding of the criteria for successful partnerships for interagency and commercial collaboration. As shown in Figure 3, each phase consists of four elements: (1) pre-work, (2) TIM, (3) analysis, and (4) deliverables. Further, central to each phase is a technical interchange meeting (TIM) facilitated by the S&T iSA facilitation and analysis team, in which representatives from the participating space agencies in the iSA collaboration topic area set objectives, discuss needs, present information or data, and make key decisions required for the goals of each phase. Briefly, phase 1 of the strategic framework focuses on establishing the overarching needs, stakeholder goals, objectives, value proposition for interagency collaboration on iSA, and strategic framework itself. Stakeholder goals communicate long-term performance targets for the S&T Partnership Forum and the Nation.

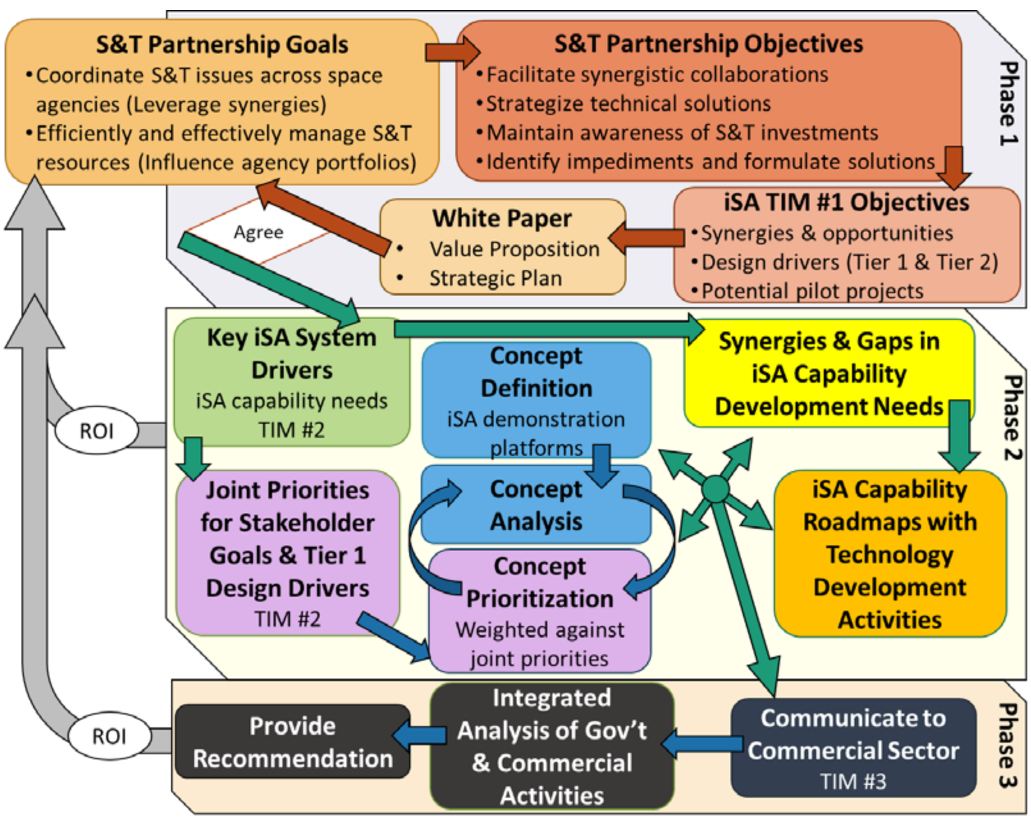

Fig. 2 Strategic framework to achieve S&T Partnership Forum goals for the iSA collaboration topic area.

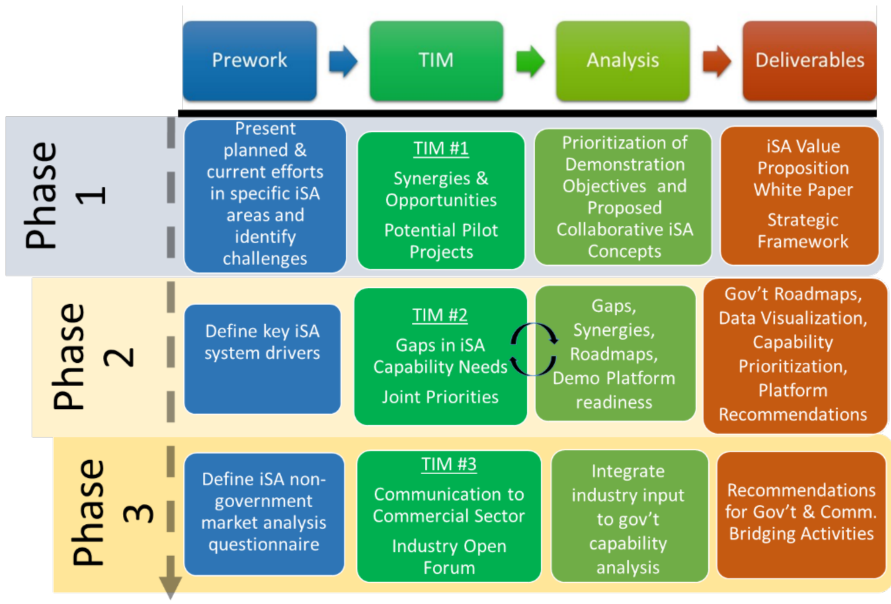

Fig. 3 The phased approach to the S&T Partnership Forum's strategic framework for the iSA focus topic.

Subsequently, phase 2 centers on the investigation of concept definitions and key design drivers for an iSA system, the identification of gaps in needed iSA capabilities and technology development among the interagency partners, concept analysis and prioritization (degree to which a capability or concept supports stakeholder goals and key design drivers identified in phase 1), and the analysis of the capabilities and gaps to develop cooperative capability roadmaps with technology development activities. A design driver for an iSA system is defined as a particular property or application of a concept or system that serves as the rationale for the concept/system's design to achieve its goal; key design drivers are those that were rated highest during a preliminary collective prioritization at the phase 1 TIM and are carried forward for analysis and discussion during the later phases. Additionally, within phase 2, a list of capability needs for iSA was generated, and technology development activities supporting those capabilities also were presented. Within the S&T Partnership Forum, a (functional) capability is defined as the ability to perform lower level functions that combine to perform tasks to assemble a mission system. It represents the basic functionality needed to perform a given iSA task. A technology is a solution that enables functional capability developments and thus the capability; multiple technologies may mature to enable a functional capability.

Finally, phase 3 examines the intersection of government and commercial objectives to provide an understanding of potential U.S. commercial and government complementary roles. Phase 3 recommends bridging activities between government and American commercial entities, based upon the integrated analysis of the data from phases 1, 2, and 3.

VI. Stakeholder Goals and Design Drivers

The data categories of stakeholder goals and Tier 1 design drivers were defined during the first TIM with the agency partners.

Four overarching stakeholder goals were defined in TIMs with the partners.

- Supports near-term demonstration: Whether a demonstration or mission could be completed within the next one or two budget cycles.
- Affordable: The ability of a mission to meet budget targets.
- Lower Cost: Whether the capabilities developed in early missions could potentially lower the cost of future missions.
- Industry Transitioning: Whether the capabilities demonstrated in missions open up a new market for commercial space entities to pursue.

At the TIM, five design drivers were designated Tier 1 design drivers, represented as the highest rated demonstration objectives.

- Stability: The tendency of a system to return to its desired state after being disturbed. Stability encompasses everything from pointing stability to the thermal stability of spacecraft.
- Assembly: The capability to assemble or construct spacecraft or space system components by joining components. This also includes the capability to assemble the system in a way that allows it to be disassembled and reconfigured into a new system or spacecraft at a future date.
- Upgradeability: Permits design choices that allow for the insertion of new technologies or enhanced capabilities after launch.
- Scalability: Has the ability to be built at different sizes or dimensions, while maintaining the same part count. For example, a segmented aperture could be scaled to a different size by changing the size or number of mirror panels but not the number of differentiated parts.
- Interfaces: Place at which independent systems transfer something to each other. This could include integrated modules, structural and thermal loads, cargo, electricity, fluids, data, and software. Interfaces are secure, cooperative, or external.

VII. Capability Needs

With the definition for capability defined as the ability to perform lower level functions that combine to perform tasks to assemble a mission system within the S&T Partnership Forum for iSA, capability needs were categorized into 14 broad capability areas, and each capability area was further decomposed into sub-capabilities. Capabilities provide the link between the technologies comprising the realization of a capability and the operational mission needs. The iSA capabilities would support or enable a specific operational mission(s) for a government agency. The participating agencies identified the capability needs for their respective agencies and, after compiling and analyzing the capabilities, the S&T iSA facilitation and analysis team carried forth a list of capability needs representing the inputs from all participating agencies. The list, shown in Table 1, serves as a part of the foundation for joint discussion and for further Forum activities within phases 2 and 3 of the strategic framework.

Table 1 Capability Needs and Their Definitions

Capability	**Definition**
1. Deployables	Structures that go from a stowed/packaged configuration to an operational configuration without external assistance
1.1 Deployable subsystems	Any deployable part, component, subsystem, etc. that is unfolded, unfurled, or otherwise moved from its stowed position, e.g., solar arrays, James Webb Space Telescope (JWST) structure, mirrors, sun shade, etc. Includes compression members (masts) and tension members (membranes, guy wires, cables)
1.2 Inflatable components	For pressure vessels such as habitats, fuel tanks
2. Structural Assembly	
2.1 Robotic assembly with joining	Use of a robotic system to attach components, subsystems, or system to each other, including both reversible and irreversible methods (e.g., screwing, latching, welding, brazing, gluing, and any other method)
2.2 Long-reach manipulation	Use of robotic arms to complete assembly tasks at a distance (>3.5 m) from the structural base.
2.3 Ability to assemble low mass structures	Ability to handle, manipulate, and join / unjoin components made from lightweight materials and/or having minimal dimensions (e.g. thickness)
2.4 Ability to assemble high strength structures	Ability to handle, manipulate, and join / unjoin components made from high strength materials and/or having robust dimensions (e.g. thickness)
2.5 Ability to assemble high stiffness structures	Ability to handle, manipulate, and join / unjoin components made from materials that have relatively high stiffness / weight even though they may not have high strength
2.6 Ability to assemble structures with micro-stable joints	Ability to join components specifically designed to hold their shape without distortion across their operational lifetime
2.7 Ability to assemble structures with high dimensional stability	Ability to use materials and designs that passively resist distortion due to operational mechanical loads
2.8 Ability to assemble structures with near isothermal control	Ability to use materials and designs that passively resist distortion due to thermal loads
2.9 Ability to assemble structures on planetary surfaces	
2.10 Ability to deploy hybrid assembly and in-space fabrication processes such as additive manufacturing	
2.11 Conductive heat transfer across assembled joints	Heat transfer limiting factor in many systems and modular heat transfer systems need development both passive and active
3. Connecting Ancillary Utilities	
3.1 Ability to route electrical power and data across assembled joints	"Joint" refers to any interface between components that were joined in space
3.2 Ability to route coaxial cables across joints	
3.3 Ability to route fiber optical conductors across joints	
3.4 Ability to route fluids across joints	
4. Ability to disjoin	
4.1 Ability to reversibly assemble structural, electrical, and fluid connections	
4.2 Ability to disconnect structural, electrical, and fluid connections without propagating damage to other system components	

5. Sensing, Modeling, Simulation, Verification	Ability to determine, either from in space or on the ground, that the system has been properly assembled and will meet performance specifications
5.1 Means of verifying the continuity of interface connections / disconnections	
5.2 Sensors to accurately and precisely measure the quality of the build-up in progress	Emphasis on in-progress. Compare with 5.3, which refers to verification and validation after the assembly has been completed
5.3 Sensors to accurately and precisely measure the as-built configuration	Checking overall conformance to design specifications
5.4 Sensors to detect failures and/or unacceptable quality of the assembly process after it has been completed	
5.5 Modeling and simulation for verification and validation	
5.6 Modeling and simulation for assembly sequencing / planning	
5.7 Quantitative performance prediction for autonomous systems	Ability to predict with known confidence the statistical performance of autonomous systems operating in uncertain environment. Alternatively, ability to quantify likelihood of system performing counterproductive or destructive operations
6. Interoperability	Ability of two systems to properly function across an interface
6.1 Standard protocols and ports to accommodate visiting vehicles and communication traffic	Hardware/operations for interoperability
6.2 Standard but secure communication protocols to accommodate interaction with other (TBD) associated systems	Software for interoperability
7. Automation / Autonomy	Ability to perform tasks and assess situation for decision making with minimal or no human input
7.1 Intelligence to make stereotyped decisions correctly without human input	Software to automate assembly operations short of full autonomy, minimal adaptability to unexpected situations
7.2 Intelligence for full autonomy	
7.3 Fail-safe modes of behavior on failure detection	Ability to detect problems and move into "safe mode" to foreclose additional problems
7.4 Multi-agent autonomy (distributed situation assessment & coordinated control)	Ability of multiple autonomous agents to develop common situation state estimate & develop appropriate cooperative plans of action w/out requiring massive real-time data links between agents
8. Precision	
8.1 Jigging and joining processes capable of achieving a high level of precision open-loop	Methods for ensuring the precision of the joining process
8.2 Known precision limits of any and all assembly agent elements across the assembly site's environmental envelope	Primarily related to changes in the thermal environment as the spacecraft orbits
9. Adaptive Correction	
9.1 Tools and approaches to alter a build-up in progress to correct build up errors	
10. Design	Methods of system design that facilitate assembly
10.1 Tools and component parts capable of accommodating a continuous spectrum of design options	Distinct from limitations based on established sizing of components and tools
10.2 Assembly agent geometries, systems, and tools that do not preclude dimensional or mass growth of the client system	Scalability

10.3 Modular design	Design with standard interfaces that allows for simple replacement of components and for re-configurability of systems by rearranging modules
10.4 Design for assembly	
10.5 Design for serviceability	
11. Tunability	
11.1 Ability to accommodate structural members with active length control	Ex: NASA JWST primary mirror movement to achieve focus
11.2 Ability to accommodate power and data control interfaces associated with active structural members	
11.3 Ability to accommodate TBD sensors for length and/or structural geometry	
12. Stability	
12.1 Ability to accommodate passive vibration damping	As a way to increase stability
13. Standard Interfaces	Common interfaces that will ensure components/systems from different providers will be able to properly connect and function
13.1 A limited number of standard mechanical, electrical, thermal, and fluid connection approaches with well-characterized properties	Standard to other systems, infers that the interface can be available to other space organizations
14. Docking/Berthing	Joining fully functional modules together either directly (autonomously or teleoperated) or with robotic assistance
14.1 Soft docking / berthing of modules	Joining of spacecraft or spacecraft modules via a mechanical interface that attenuates any relative motion between modules. The interface is usually a docking ring. Ex: manned-space vehicle docking or joining of ISS pressurized modules. Includes any rendezvous and proximity operations

VIII. Conclusion

In summary, this paper describes an overview of the S&T Partnership Forum, an interagency collaboration effort among NASA, the USAF, the NRO, DARPA, and the NRL. The S&T Partnership Forum serves to coordinate and facilitate partner dialog, collect data and perform data analysis, and assemble data products into recommendations for partnerships to be executed within the S&T community at the program and project levels within the partnering agencies. Further, the paper describes the S&T iSA facilitation and analysis team's coordination efforts for the iSA collaboration topic area within the Forum. The team's efforts within phases 1 and 2 of the iSA collaboration strategic framework generated a list of capability needs, stakeholder goals, and design drivers, described herein as well. Collectively, the stakeholder goals, key design drivers, and iSA capability needs form the basis of reference for: (1) the current efforts by the S&T iSA facilitation and analysis team within phase 2 of the S&T Partnership Forum strategic framework for iSA and (2) future activities in phase 3 as the S&T Forum engages the commercial sector to identify complementary opportunities for commercial entities to pursue within iSA. Specifically, two of the phase 2 efforts include: (1) data collection and analysis on iSA capabilities, including the development of government roadmaps for iSA efforts and (2) the prioritization of iSA capability needs against the stakeholder goals and design drivers to inform potential demonstration concepts for achieving, advancing, and maturing iSA capabilities via interagency collaboration. Preliminary results of these two efforts are detailed in *Arney et al. (2018)* [2] and *Hamill et al. (2018)* [3], respectively.

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