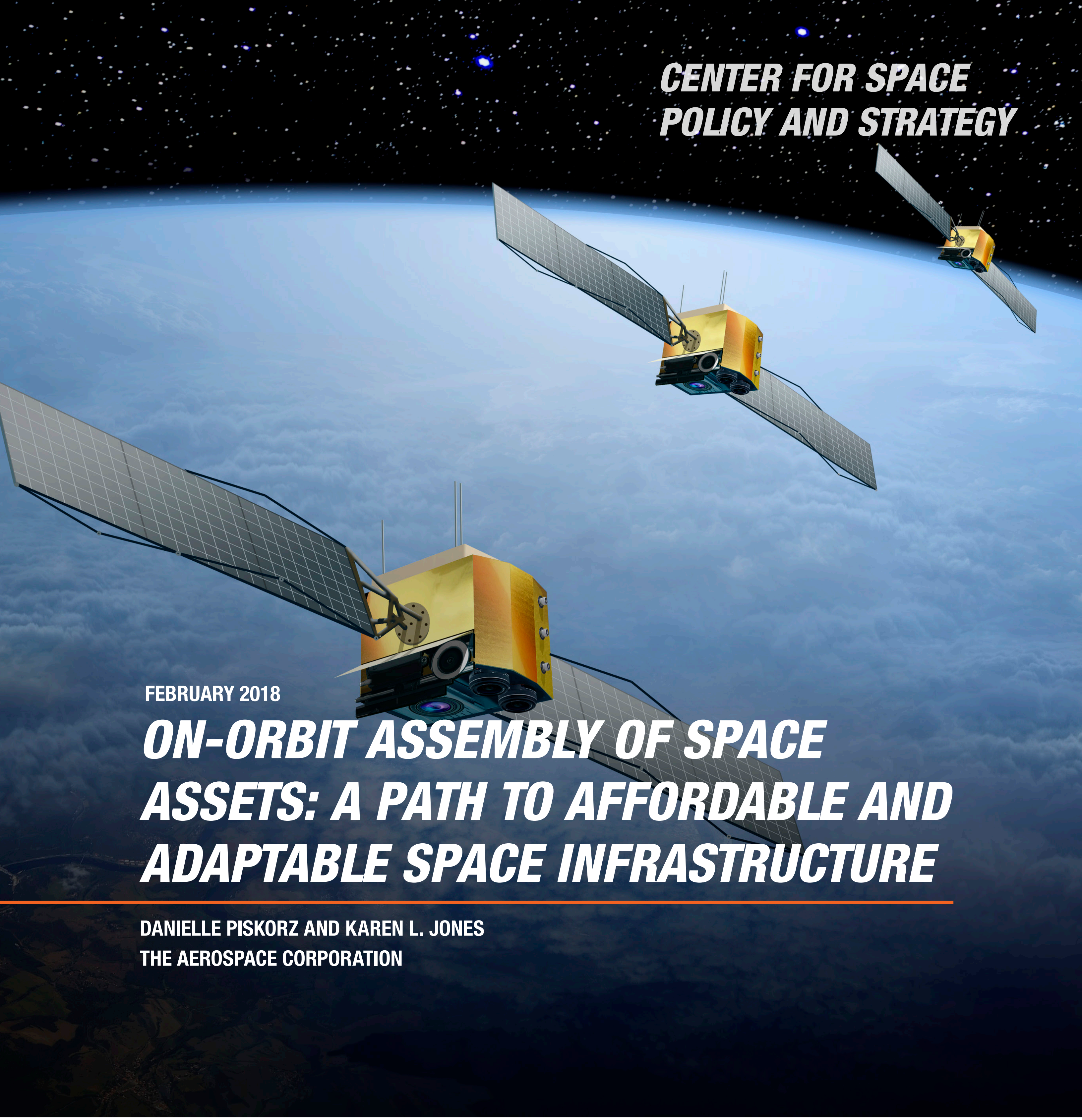

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ON-ORBIT ASSEMBLY OF SPACE ASSETS: A PATH TO AFFORDABLE AND ADAPTABLE SPACE INFRASTRUCTURE

DANIELLE PISKORZ AND KAREN L. JONES
THE AEROSPACE CORPORATION

DANIELLE PISKORZ

Dr. Danielle Piskorz is a member of the technical staff in The Aerospace Corporation's Visual and Infrared Sensor Systems Department. She provides data and mission performance analysis in the area of space situational awareness. Her space policy experience derives from positions at the Science and Technology Policy Institute and the National Academies of Sciences, Engineering, and Medicine, where she contributed to a broad range of projects in commercial and civil space. She holds a Ph.D. in planetary science from the California Institute of Technology and a B.S. in physics from Massachusetts Institute of Technology.

KAREN L. JONES

Karen Jones is a senior project leader with The Aerospace Corporation's Center for Space Policy and Strategy. She has experience and expertise in the disciplines of technology strategy, program evaluation, and regulatory and policy analysis spanning the public sector, telecommunications, aerospace defense, energy, and environmental industries. She has an M.B.A. from the Yale School of Management.

CONTRIBUTORS

The authors would like to acknowledge contributions from Roy Nakagawa, Henry Helvajian, and Thomas Heinsheimer of The Aerospace Corporation and David Barnhart of the University of Southern California.

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Abstract

On-orbit assembly is an important step toward the proliferation of highly adaptable and capable space infrastructure. Space capabilities for both traditional and new stakeholders will be revolutionized by the ability to assemble modular building blocks into a functional and complex infrastructure. To succeed, these building blocks must be compatible and interoperable, with some level of autonomy; however, there is currently no governance for establishing standards in key areas that enable on-orbit assembly (e.g., mechanical, electrical, power, thermal, and data interfaces).

A goal of the 2010 U.S. National Space Policy is to "promote a robust domestic commercial space industry" and "foster fair and open global trade and commerce through the promotion of suitable standards and regulations that have been developed with input from U.S. industry."[1] To spur the development of innovative on-orbit assembly, stakeholders should anticipate the needs of the increasingly diverse space industry and act to establish interface standards. The future of assembly-driven architectures will be determined either by incompatible national and industry-proprietary solutions, or by a cooperative path toward open architectures based on compatible, interoperable building blocks.

This paper seeks to explain the pressing need for interface standards for on-orbit assembly, outline current efforts to achieve this objective, discuss policy implications of on-orbit assembly, and propose an initial roadmap for the on-orbit assembly community.

Drivers for On-Orbit Assembly

Growing interest in on-orbit assembly is influenced by two key factors. The first is the proliferation of low-cost launch vehicles. The second is the expected ease of autonomous rendezvous and docking of small and mid-size satellites. This leads to architectures in which large spacecraft are no longer "built big" on the ground and launched by massive boosters, but are instead assembled on-orbit through successive launches of autonomous units and other small components.

On-orbit assembly circumvents many of the limitations on satellite size and mass (and ultimately capabilities) posed by the launch environment.[2] For example, the size of a rocket faring limits the size of the objects launched, resulting in complicated designs for large satellites (e.g., the unfolding 6.5-meter James Webb Space Telescope designed to fit into a 5-meter Ariane rocket faring[3]). In addition, launching satellite components implies that less of the mass within the rocket will have to be devoted to carefully packaging a large satellite so that it survives launch. The ability to launch satellite components also reduces the need for many ground-based preflight integrated system tests and eliminates gravitational constraints on massive spacecraft.[2] Finally, on-orbit assembly provides many opportunities for increased mission flexibility and resilience by avoiding the constraints of rigid launch manifests.

From the "Wild West" to Consensus Standards

On-orbit assembly is still in the nascent stages of development, with multiple competing noncompatible systems and little to no oversight. A set of well-conceived industry standards in this area could allow emerging space participants to access new markets and allow existing space participants to expand their capabilities. For all space participants, standards facilitate global collaboration—an increasingly important concern.

> ***It is difficult to impose standards in a mature industry where participants have already made significant investments…***

And yet, as beneficial as standards may be, the timing of their implementation can profoundly affect their widespread adoption. It is difficult to impose standards in a mature industry where participants have already made significant investments in proprietary designs and associated manufacturing and supply chain interests. This was the case for the Space Universal Modular (SUMO) architecture,[4] which sought to standardize satellite components for the nearly $100 billion U.S. satellite industry[5] in 2012. SUMO was unable to gain acceptance from key government stakeholders and space bus manufacturers, who already owned mature proprietary designs. If a market is immature (as is the case for the emerging on-orbit assembly market), then fewer vested equities exist and standardization becomes less costly; however, it should be noted that if standards are created too early in the technology development cycle, it could be more difficult to discern the best and most appropriate standard.

A variety of space assembly prototypes are being assessed and tested through government and industry collaboration. The on-orbit assembly industry is currently transitioning from applied research on the ground to experimental development; launches of new on-orbit assembly missions are imminent. This is a propitious time to begin the early stages of standards development.

Current State of the Art

One of the earliest and grandest examples of on-orbit assembly is the International Space Station (ISS), a spacecraft the size of a football field constructed over 20 years with dozens of industry and international partners.[6] Various ISO (International Organization for Standardization) technical committees and subcommittees oversaw the development and design of the requisite interfaces, including aircraft and space vehicles, space data and information transfer systems, and space system operations.[7] Before and since its completion, the ISS has been an important nexus for innovation and exploration.

Advancements in robotics, artificial intelligence, and miniaturization of systems, as well as the rise of commercial launch and satellite enterprises, suggest that future on-orbit technology will be more autonomous and industry-driven. Current efforts can be divided into on-orbit servicing and on-orbit assembly (Figure 1). On-orbit servicing involves activities that extend the life or value of a spacecraft already in orbit, whereas on-orbit assembly involves the creation of a new asset from modular (and likely autonomous) components. In both cases, industry growth and international collaboration will strongly depend upon the effective implementation of technical standards. Here are a few of the more intriguing developments in these two areas (based on the companies' descriptions of their own work).

On-Orbit Servicing

- **DARPA RSGS.** In February 2017, DARPA selected Space Systems Loral (SSL) to develop technologies to enable cooperative inspection and servicing of satellites in geosynchronous orbit (GEO), collectively called the Robotic Servicing of Geosynchronous Satellites (RSGS) program. The first commercial client is SES,[8] which will employ the robotic servicing vehicle to perform inspections, correct mechanical problems, install new payloads, and relocate and refuel the spacecraft. RSGS is being designed to service national security assets and will fly before the end of the decade.[9]
- **NASA/SSL Restore-L.** The Restore-L mission is planned to launch in mid-2020 and will perform an autonomous rendezvous with Landsat-7 in low Earth orbit (LEO) followed by refueling and orbit

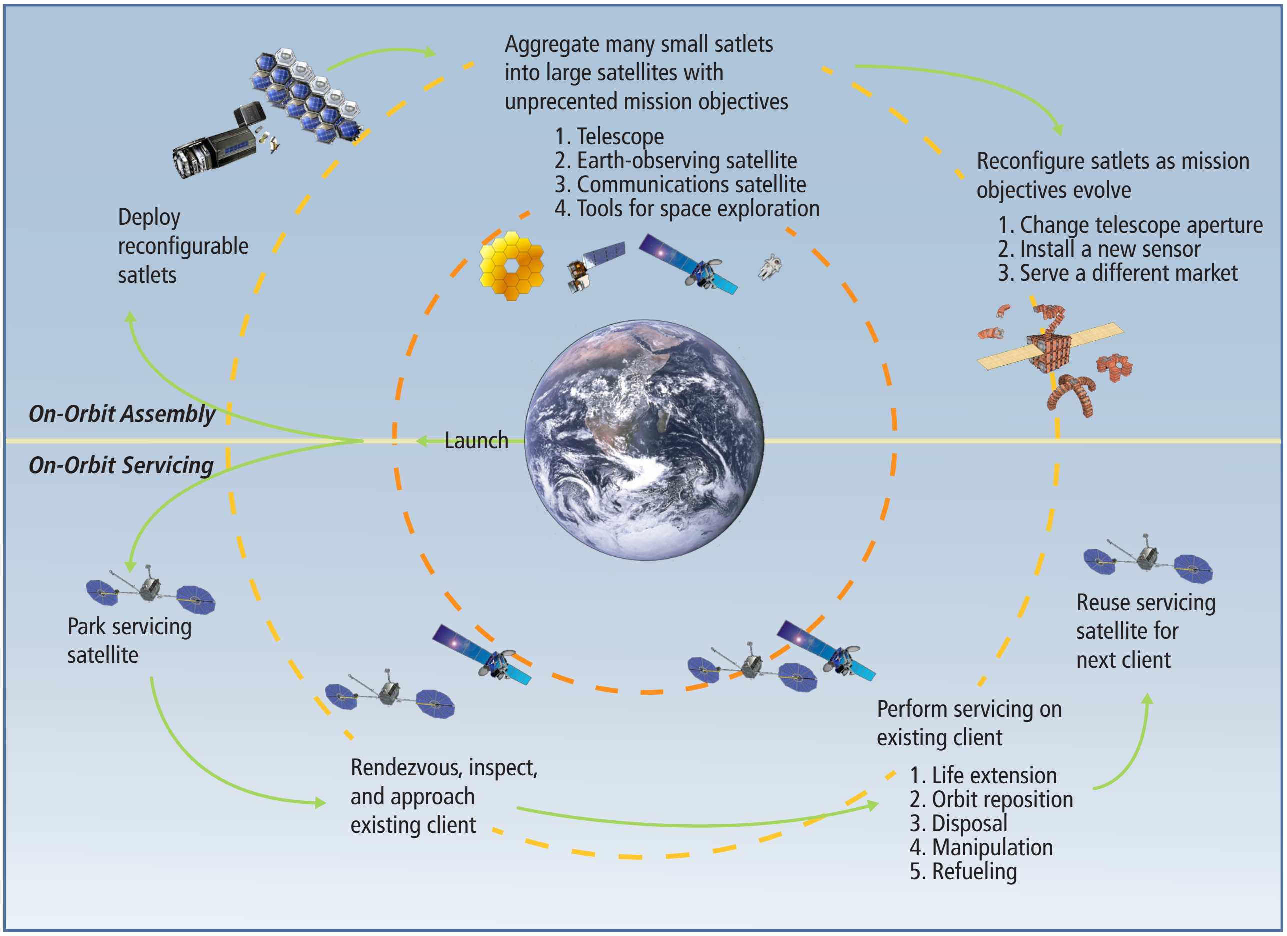


Figure 1: Distinction between on-orbit assembly and servicing paradigms (*adapted from David Barnhart, USC*).

relocation. This endeavor requires two robotic arms and the development of a reliable propellant-transfer system.[10] Landsat-7 is an unprepared client, not originally designed with on-orbit servicing in mind, and its functional lifespan will be lengthened by this servicing mission.

- **Northrop Grumman/Orbital ATK MEV.** The first Mission Extension Vehicle (MEV-1) is on track to launch in late 2018 and will provide services for Intelsat. MEV-1 will dock with the satellite and run an orbit-maintenance and attitude control-program before undocking and moving on to another satellite. MEV-1 is designed to service multiple satellites over 15 years.[11] The spacecraft's docking system is reportedly compatible with 80% of GEO satellites currently on orbit.[12]
- **Airbus Space Tug.** Airbus has announced its intention to enter the satellite servicing market and develop a Space Tug that will refuel satellites and remove debris.[13]
- **DLR DEOS.** Run by the German aerospace agency DLR, the Deutsche Orbitale Servicing (DEOS) mission aims to demonstrate servicing capabilities in 2018. Two satellites will be launched, a client and a servicer. The servicer will capture the "uncooperative" client, dock with it, refuel it, exchange modules, and deorbit it.[14]

On-Orbit Assembly

- **DARPA Phoenix Technologies.** This program involves development of several new technologies for on-orbit servicing and assembly, one of which is focused on modular units. Each unit has key capabilities; shares data, power, and temperature control; and could be rearranged to achieve changing mission objectives.[15] The first generation of these mini satellites—called Hyper-Integrated Satlets, or HISats—were produced in partnership with NovaWurks. In October 2017, astronauts onboard the ISS assembled and launched a satellite consisting

Examples of Interface Standards

Standardization encourages compatibility and interoperability, avoiding lock-in of old technology and boosting the efficiency of supply chains. In addition, standards build cohesion and critical mass in emerging markets, thereby enabling competition and product variety. The following two examples embody these attributes:

- **Shipping containers.** The use of standard shipping containers has reduced freight costs, shipping times, labor costs, and damages to transported goods by promoting the integration of various forms of transportation. The same container can be transported around the world on a ship, train, or truck.[17] For on-orbit assembly, this is reminiscent of the "freight-train-to-space" concept where satellites and their components are efficiently and routinely launched and assembled on-orbit, made possible by industry standards.
- **Universal serial bus.** The universal serial bus (USB), a peripheral standard hardware interface created by an industry consortium, revolutionized the computer peripheral market. An interface akin to a USB standard for on-orbit assembly would encourage creative services and solutions while opening up a wide range of technical possibilities and mission objectives.

of six HISats, two solar arrays, and a modularized electro-optical imager.[16] In 2018, a related mission called eXCITe (Experiment for Cellular Integration Technologies) will evaluate the strength of HISat interfaces during launch and their functionality on orbit.[18] In combination with another Phoenix technology, the standardized Payload Orbital Delivery (POD) system (which can support 100-kg payloads), the Phoenix program seeks to improve satellite resilience and lower the cost of construction and deployment.[19]

- **The Aerospace Corporation Hive.** The Hive concept is based on a mass-producible CubeSat that can rotate a "face" while attached to other Hive units. This allows one unit to "climb-over" others via prehensile action and thereby change the morphology of the ensemble. The Hive concept is now undergoing engineering feasibility studies.
- **SSL Dragonfly.** The Dragonfly concept involves the semi-autonomous robotic assembly of GEO communications satellites, launched as a whole but requiring final assembly on orbit. In September 2017, SSL demonstrated the Dragonfly concept on the ground using a highly dexterous robotic arm and advanced command and control software.[20] This 3.5-meter arm can operate controls at either end of the robot.[21] The next step is to apply these capabilities to on-orbit operations and drive on-orbit assembly of GEO satellites. Benefits could include higher satellite performance through assembly of a larger antenna and greater mission flexibility through the ability to move or change a satellite's antenna.[22]

Eventually, on-orbit assembly might extend to interplanetary exploration—for example, setting up launch pads on the surface of Mars, or using reconfigurable robots to provide timely reconnaissance on a planetary surface and reduce mission risk. With appropriate shared vision, public and private stakeholders in the on-orbit assembly community can devise building blocks with compatible mechanical, electrical, power, thermal, and data interfaces to enable the construction of large structures in space.

Standardizing Interfaces for On-Orbit Assembly

Though on-orbit assembly is at the "Wild West" stage,[23] the concept is gaining traction from a technological and architectural perspective. The adoption of interface standards will mitigate risks and allow for repeatable operations, permitting missions to take full advantage of the on-orbit assembly paradigm.

Standardization of the following critical interfaces could facilitate efforts to advance on-orbit assembly:

- **Mechanical.** Similar to the intermodal container industry, standards for mechanical interfaces between modules have the potential to generate new applications for spacecraft built on-orbit. Given the ability to pop off one module and pop on another, a spacecraft's mission becomes flexible and adaptable as obstacles arise and objectives change. An example of an on-orbit mechanical interface is the docking of modules and spacecraft with the ISS.

- **Electrical.** The wiring in the design and construction of modules must be consistent to ensure reliable connections between modules when assembled. A current popular electrical interface is SpaceWire, used in many ESA missions and some NASA missions.[24]
- **Power.** Standards for power interfaces encompass a plug-and-play capability for a power supply, extending a satellite's lifespan or providing extra power during an emergency or a complicated maneuver.
- **Thermal.** Standards for thermal interfaces permit the transfer of heat among modules, reducing overheating or overcooling and increasing service life.
- **Data.** A data-interface standard would ensure that information can be efficiently transferred between modules with little loss. These communication capabilities might occur over wireless links for connected modules or modules in the process of self-assembly. Reliable data interfaces are critical for rendezvous and proximity operations as well as for software compatibility.

Interface standards need to address a number of component attributes. In particular, the community should foster development of systems that are:

- **Secure and protected.** A secure and protected interface thwarts unwanted attempts to remotely or physically control an asset or gain access to its data.
- **Modular.** A modular interface ensures that the various pieces of the final satellites are inherently interchangeable. This encourages innovation and development of new capabilities.
- **Interoperable.** An interoperable interface establishes functionality between modules, allowing for a straightforward exchange of data and power.
- **Open.** An open interface enables international cooperation and innovation. The intricacies of an open interface are transparent to its users.
- **Industry-friendly.** An industry-friendly interface encourages full participation and innovation from the space industrial base. This includes examination of intellectual property, and might require that all interfaces and standards be in the public domain, even if components behind those interfaces are proprietary.

Paths to Standardization

Interface standards are often set when a technology or capability transitions from applied research to experimental development. Then, as the technology or capability is widely diffused, standards for compatibility and quality become critical.[25] However, the specific path to standardization is difficult to predict. In order of decreasing formality, general options for the implementation of standards include:

- **Standards development organization:** a formal body that develops and disseminates standards to its users. Prominent examples are the International Organization for Standardization (ISO) and Consultative Committee on Space Data Standards (CCSDS).
- **Consortium:** a less formal version of a standards development organization. Examples are the consortium that developed the USB standard and the Consortium for Execution of Rendezvous Servicing Operations (CONFERS).
- **De facto industry standards:** an informal method for choosing an industry standard. Here, a dominant technology leader's hold on the market forces the rest of the market to adopt its standard. De facto standards can also be adopted if they are historically widely used (e.g., QWERTY keyboards) or if they are extremely efficient (e.g., PDFs).

The development of on-orbit industry standards across these five categories having the above five attributes could encourage a more adaptable and affordable exploration and exploitation of LEO, GEO, and interplanetary space.

Progress to Date and Path Forward

A number of organizations are starting to develop standards that will affect rendezvous and proximity operations. These could evolve into international standards over time, and many will have tremendous relevance for on-orbit assembly. Still, these organizations have, to date, focused on requirements and standards for on-orbit servicing and not for on-orbit assembly.

For example, wireless standards are rapidly maturing and are key enablers for rendezvous and proximity operations. The international Consultative Committee on Space-Based Data Standards (CCSDS) has developed various standards, recommended practices, and information reports to support spaceflight collaboration (both planned and contingency) throughout industry and government.[26] The CCSDS standardization process is intended to encourage commercialization and cost sharing. The committee's technical area is spacecraft onboard interface services, and within this area, there are many standards and best practices to explore, especially in network wireless communications in space.[27]

In October 2017, DARPA awarded a contract to Advanced Technology International to organize and manage the Consortium for Execution of Rendezvous and Servicing Operations (CONFERS).[28] The consortium consists of the Secure World Foundation, the University of Southern California, and the Space Infrastructure Foundation.[29] This collaboration will address the issue of rendezvous and proximity operations for on-orbit servicing, leverage experience in the public and private sector, and develop and publish consensus operational safety standards for rendezvous and proximity operations.[30] Ultimately, the consortium's draft standards will be passed up to the formal standard development organizations ISO and CCSDS.

In addition to formal standards development, the Interagency Operations Advisory Group (IOAG) provides a forum for representatives from various national space agencies and working groups to coordinate communications and technical interfaces to promote interoperability.[31] Some of their recent initiatives include promoting the use of the 26 GHz band for downlinked data from LEO, establishing a process to provide emergency support to spacecraft, and studying scenarios for the interoperability of optical communication.[32]

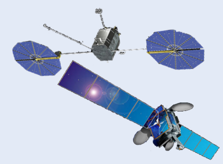
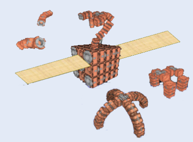
The development of industry-consensus standards for on-orbit assembly will enable a more adaptable and affordable exploration of near-Earth space and other planets. Table 1 provides a "crawl-walk-jog-run" roadmap and associated direct benefits that result from an open, modular, and universal architecture.

Other Policy Implications

There is more work ahead for the on-orbit assembly industry aside from the development and adoption of interface standards. Important political challenges could potentially hinder development from both a technological and a programmatic standpoint. These include concerns about:

- **National security.** On-orbit servicing and assembly is likely to take a strong commercial foothold worldwide, and the "openness" desired by many commercial firms might be viewed as a serious risk by those in the national security community. There may be fears that adopting open standards for national security missions could create vulnerabilities, or even that large-scale commercial adoption of these standards could leave large populations of satellites susceptible to exploitation by commercial or military rivals. These potential vulnerabilities underscore the importance of establishing secure or protected inter face standards.
- **ITAR.** The International Traffic in Arms Regulations restrict the sharing of defense-related technologies by U.S. entities with foreign entities. This may hinder international collaboration as on-orbit assembly technologies are developed, but may also protect U.S. assets and intellectual property.
- **Government participation.** The government must ensure that it is involved in the development and implementation of voluntary consensus standards. The Office of Management and Budget provides guidance to agencies as standards are selected and directs the National Institute of Standards and Technology (NIST) to coordinate standards and assess conformity.[33]
- **Protection of intellectual property.** As is the case for many space technologies, the government must make a commitment to protect intellectual property rights. The U.N. "Declaration on International Cooperation in the Exploration and use of Outer Space for the Benefit and in the Interest of All States" specifically calls out "intellectual property rights" as an example of the "legitimate rights and interests" for cooperative ventures in space.[34] With growing private-sector participation in outer space, stronger

Table 1: Preliminary Roadmap for On-Orbit Assembly Ventures

	Phase			
	Crawl	**Walk**	**Jog**	**Run**
Goal	Human-in-the-loop on-orbit servicing and assembly 	Inter-vehicle on-orbit assembly (i.e., servicing) 	Intra-vehicle on-orbit assembly 	Space fleets for planetary exploration 
Demonstration examples	• Construction and servicing of the International Space Station with more than 1000 hours of space walks • Servicing of the Hubble Space Telescope	• On-orbit repair of malfunctioning satellites through removal and replacement of initially external systems in LEO and GEO, followed by satellite design changes to allow complete refurbishment	• On-orbit assembly, reconfigurability, and property function transferability with an assembly of mass-producible CubeSats and an evolving "smart" interconnect interface	• Reconfigurable telescope • Reconfigurable moon outpost • Reconfigurable Mars surface vehicle
Key capabilities	• Basic procedures and best practices for zero-gravity construction and interface development • Some standardized mechanical interfaces for docking of modules and spacecraft	• Short-range wireless links and networking as well as external vehicle-to-vehicle proximity communication wireless links and networking (up to a few 100 m in range) • Some standardized mechanical and power interfaces	• Inter-component (on same vehicle) communication, short-range wireless links, and networking capabilities • Widespread standardized mechanical, electrical, power, and thermal interfaces	• Longer-range wireless links • Completely autonomous assembly
Benefits	• Foundations for international and industry collaboration • "Safe" learning environment	• Technology refresh • Life extension • Reduced costs • Reduced risks	• Unprecendented mission flexibility • Reduced spacecraft complexity • Ease of entry into market • Variety of spacecrft capabities • Reduced costs • Reduced risks	• Large and modularized exploration missions built to match (inter)national budget cycles
Working groups	• ISO (sub)committees • NASA • Other international space agencies	• CONFERS • CCSDS • IOAG	• None to date	• None to date

protection of intellectual property rights are needed to encourage industry participation and maintain the pace of innovation.

- **Disclosure of intellectual property.** There is a natural tension between standards and intellectual property; standards focus on leveling the playing field and sharing open commonalities, while intellectual property focuses on preserving exclusive rights to an invention. Various strategies can be applied to balance these opposing forces. For example, the International Telecommunication Union allows the use of patented technology in standards if the patent is disclosed before selection of the standard.[35] Still, anti-competitive behavior can be difficult to rein in, and this underscores the need for a timely adoption of standards, if only as a strategy to maintain fairness in the market.
- **Damage liability.** The complicated, autonomous rendezvous and proximity operations that occur during on-orbit assembly are likely to cause at least occasional damage to spacecraft. In fact, a satellite near the end of its operational life may not be insured but still suitable for refueling; servicing such a satellite would require a contingency plan if the servicing activity were to disrupt the satellite's orbit.[36] If an operation involves separate organizations, there will need to be a framework in place that protects the owners of the space assets involved and perhaps enables an independent entity to monitor the operations.

Conclusion

On-orbit assembly promises to enhance spacecraft capability, increase mission flexibility, reduce risk to assets, and promote a vision for continuous operations and upgrades. Modular systems are evolving now through proof-of-concept designs from DARPA, SSL, Northrup Grumman/Orbital ATK, and others and through collaborative standards organizations such as CONFERS, CCSDS, and IOAG. These early efforts will lay the foundation for the policies and frameworks that will support reconfigurable robotic technology for on-orbit assembly.

Galvanizing the space industry to cooperate and set interoperable standards is a monumental endeavor—which, if successful, could forge the next great steps in space exploration and innovation. As industry continues to develop on-orbit assembly missions, leading space organizations can take an anticipatory approach toward setting an industry-consensus standard for a set of interfaces to foster innovation, efficiency, and growth. Common mechanical, electrical, power, thermal, and data interface standards must be secure, protected, modular, interoperable, open, and industry-friendly. In doing so, security concerns, current vested equities, and future stakeholders must all be considered.

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