Toward a Fully Capable In-Space Manufacturing Ecosystem

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As technology for in-space refueling and servicing continues to mature, in-space assembly and manufacturing efforts can expand to leverage these new capabilities. This paper expands upon previous work and describes four use cases for a fully capable in-space manufacturing ecosystem. Based on those use cases, enabling technology areas are identified and shortfalls in those technologies are noted for seven key categories. Finally, a survey of options for in-space experiments and demonstrations are presented, showing pathways for technology development in relevant environments.

I. Introduction

Achieving a sustainable and resilient in-space ecosystem will require infrastructure not possible using current terrestrial manufacturing processes and existing space lift capabilities. Establishing in-space manufacturing facilities that can produce satellites, modular components, and other systems on-demand will greatly expand flexibility while also mitigating emerging threats from those hostile toward freedom of action in space. This strategy can also generate cost savings by eliminating the need to design spacecraft that need to survive launch loads, thus reducing the scope of required assembly, test, integration, and scheduling activities. Further, the approach allows for the design of extremely large aperture antennas or optics which are not limited to the confines of the payload fairing.

The pace of activities related to in-space servicing, assembly, and manufacturing (ISAM) continues to accelerate, especially as government agencies refine their plans following the publication of the ISAM National Strategy [1] and the National ISAM Implementation Plan [2]. The original NASA OSAM State of Play [3] now has a follow-on report [4] covering recent updates to the field. Notably, the United States Space Force (USSF) and its Space Systems Command have publicly described their interest in the potential benefits of mission life extension through refueling and servicing [5]. This interest is translating into action with a recent example comprising a contract agreement with Astroscale to develop a refueler which will transfer fuel between a geostationary depot and a client satellite [6].

The ability to rendezvous with existing space vehicles and refuel them is generally viewed as the foundational capability for the other aspects of ISAM, and tremendous progress has been made toward that goal. Northrop Grumman has accomplished successful rendezvous and docking with existing satellites using its Mission Extension Vehicles (MEV) on two separate occasions [7, 8]. Astroscale recently completed a successful rendezvous with its target as part of its Active Debris Removal by Astroscale-Japan (ADRAS-J) mission [9].

In-space manufacturing and assembly are long-term capabilities that, if achieved, would provide significant asymmetrical advantage beyond just in-space refueling. To attain these goals, advancements must be made to enable continuous sustainment, resupply, provision of logistics, and maneuvering capability. Ultimately, the capabilities will provide operational flexibility, faster and more frequent access to more distant orbital locations, and freedom to maneuver to achieve objectives. While assets today operate in static orbits, the future will involve assets which can maneuver without regret in the space domain. Upgrading and repairing via modularity will enable high-performance processing, upgrades of electronics and sensors without launching a new spacecraft, evaluation of new capabilities that evolve along with missions, and longer life spans by replacing impaired components.

The potential to fabricate new capabilities on orbit is growing more and more likely. However, much work is required to ensure the needed technologies will be ready when customers require them. There are unique considerations for

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Fig. 1 Orbital satellite factory concept of operations.

manufacturing that should not be delayed as we await refueling and other servicing capabilities to materialize. It is wise to identify technologies that can be advanced on a parallel path to ensure that in-space assembly and manufacturing are realized as quickly as possible. This paper continues previous work with the overarching goal of moving the ISAM community forward by identifying as many gaps and challenges as possible. It expands on the previous roadmapping effort for smallsat construction and considers multiple use cases for a complete in-space manufacturing ecosystem. After identifying required technologies and their current states, the paper highlights several pathways to advance maturity through in-space experiments and demonstrations.

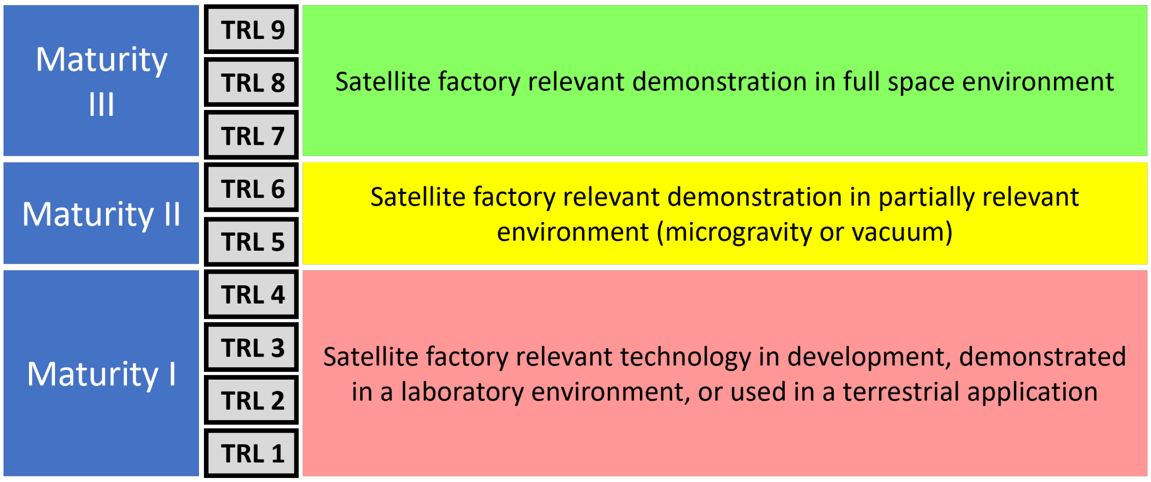
II. Previous Work

A. The Orbital Smallsat Factory Concept

The original concept for the orbital satellite factory (OSF) [10] proposed a persistent platform which would accept and store raw materials and terrestrially manufactured components, manufacture the structural and electrical backbone of a product space vehicle, and then assemble the completed product. An illustration of this concept of operations (CONOPS) is shown in Fig. 1. The original concept centered around four key technologies: fused filament fabrication (FFF), laser soldering, wire embedding, and pick-and-place robotics. The overarching idea was to employ the concept of hybrid additive manufacturing (AM) to form the baseline manufacturing capability.

B. Orbital Smallsat Factory Technology Roadmap

Further consideration of the technologies needed to produce a functional smallsat in orbit revealed that the span of capabilities required was considerably larger than first presented. The follow-on work expanded the list to 24 technology areas divided into 6 different groups: manufacturing, materials, assembly, inspection, factory operations, and satellite operations [11]. For each of these areas, a review of past, current, and planned work was conducted. Subsequently, each technology was evaluated to assess its developmental maturity using the scale shown in Fig. 2. Maturity Level I is roughly equivalent to TRL 1 through 4 and indicates technologies that are in the research or laboratory demonstration phase. Maturity Level II, roughly TRL 5 and 6, corresponds to technologies which have been demonstrated in relevant environments or those that partially capture the complete environment of the end use case.



Maturity III	TRL 9 TRL 8 TRL 7	Satellite factory relevant demonstration in full space environment
Maturity II	TRL 6 TRL 5	Satellite factory relevant demonstration in partially relevant environment (microgravity or vacuum)
Maturity I	TRL 4 TRL 3 TRL 2 TRL 1	Satellite factory relevant technology in development, demonstrated in a laboratory environment, or used in a terrestrial application

Fig. 2 Maturity readiness levels for factory-relevant technologies.

Maturity Level III technologies are those which have at a minimum been demonstrated in a space environment, meaning the TRL is 7 or above. A more complete picture was formed by also considering the criticality of each technology to the establishment and execution of the satellite factory. To facilitate this approach, three criticality ratings were identified for the previously outlined technologies. Criticality I technologies are the most critical and are those which are required to demonstrate the full assembly of a product satellite. Without these, individual or modular components cannot be attached together to form a completely functional satellite. Criticality II technologies are those which are either required to manufacture components in orbit or required to verify the proper construction of the product satellite. Finally, Criticality III technologies are those which would increase the longevity of the satellite factory, the longevity of the product satellites, or both. These assessments were combined on the matrix shown in Fig. 3. The overall result of this work is a holistic picture of the current state of in-space manufacturing that can be used to draw conclusions about developmental priorities and identify value-added paths forward.

III. In-Space Manufacturing Use Cases

The focus of this iteration of the roadmap is to consider not just a stand-alone factory for smallsats, but also the surrounding capabilities needed to produce and service larger space vehicles and structures. To develop the guiding needs for this manufacturing ecosystem, several use cases are in development. These use cases are introduced in this section.

A. Use Case 1: In-Space Manufacturing of Larger-than-Launchable Structures

The first use case involves the need to build structures unconstrained by fairing size. There are a number of potential applications where persistent space platforms would be enabled by in-space assembly and manufacturing, For example, the 2018 NASA In-Space Astronomical Telescope study emphasized that in-space assembly can enable observatory sizes not achievable by conventional, single launch approaches while providing opportunities to reduce costs for observatories with aperture diameters of 5 to 15 meters [12]. Another potential advantage exhibited by this scenario is the ability to build structures that will not survive launch loads when fully assembled or configured in a pre-deployment form.

As the Low Earth Orbit (LEO) ecosystem continues to evolve to match terrestrial capabilities, infrastructure becomes a fundamental asset. Even with the promise of larger scale launch fairings, structures developed on Earth's surface and compacted into fairings may impose a ceiling on the possibilities of microgravity construction. Structural elements will tend towards cylindrical design and will inherently restrict themselves upon the need to survive the launch environment. Packing efficiency will be limited, as pre-built structures with any interior volume will incur the opportunity cost of additional material that could have otherwise been launched as part of a solid structure. In pursuit of larger-than-launchable structures, orbital manufacturing is a necessity.

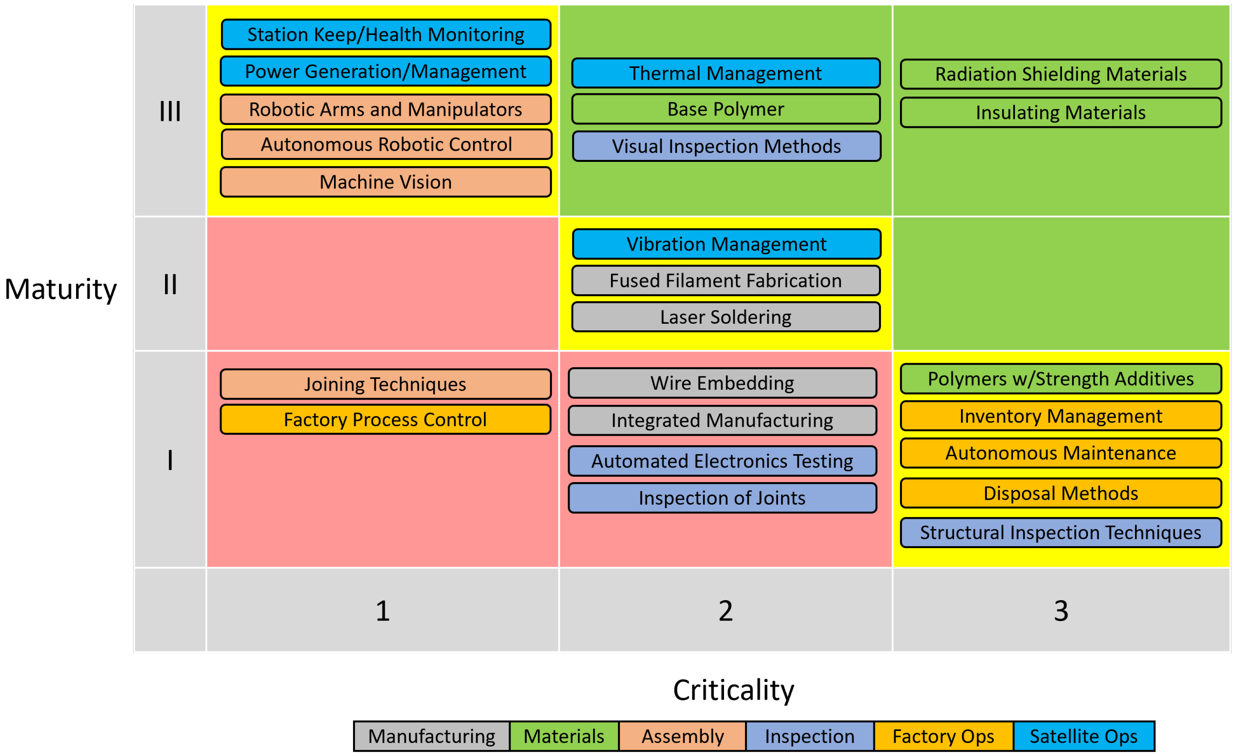


Fig. 3 Maturity and criticality matrix for smallsat factory technologies.

1. Unique Offering of In-Space Manufacturing

Considering the impacts of orbital manufacturing, the scope of large structures can be widened. With broader, less restrictive designs imposed by launch fairing limitations, structural material can be utilized more efficiently and more adequately in the space environment. Not only does microgravity reduce imperfections in certain additive manufacturing techniques, the microgravity environment means that structures can be designed as largely and as freely as necessary. It still may be worthwhile to terrestrially manufacture and launch more complex components and systems, but the structural framework needed to enable larger-than-launchable systems can be produced much more efficiently on orbit. Utilizing raw materials refined on earth, packing efficiency can increase volumetrically within launch vehicles so that these structures can be developed without a prohibitive number of launches. With a large quantity of efficiently launched mass, in space manufacturing technologies can leverage these resources to begin developing structures as they are needed.

2. Timeline and Concept of Operations

1) Development organization begins project.
2) Development organization contracts orbital manufacturing operator, launch vehicle provider, and orbital servicing operator.
3) Launch vehicle provider launches raw material conducive with orbital manufacturing techniques (metallic wiring, metal powders, polymer filament, etc.).
4) Orbital manufacturing operator leverages raw material and begins production of large structures.
5) Once large structures are complete, development organization leverages launch vehicle provider to launch complex components.
6) Orbital servicing operator transports and integrates complex components to large structures.
7) Operations cycle continues as needed until all requisite components are manufactured, launched, and integrated.

B. Use Case 2: Rapid Deployment of a New Sensor Suite

An additional use case to emerge is the rapid deployment of a new sensor suite when launch opportunities are constrained. In this scenario, a provider has developed a new sensor suite that may drastically improve capabilities in support of the end user. There is an immediate need to deploy these sensors to maintain needed capability. The sensors do not require specialized integration or assembly and can be easily mounted on standard small spacecraft platforms. Coverage analysis shows that a network of 20 distributed sensors are required on-orbit. In the short term, launch providers are nearly fully subscribed with other high-value missions and only one launch can be scheduled in the next year.

1. Unique Offering of In-Space Manufacturing

An operational OSF would provide a unique opportunity to satisfy the mission need given the constrained launch environment and the immediate need. The OSF would pick out a sensor from a stock batch manufactured and launched from Earth on the sole available launch and integrate it onto a satellite platform manufactured and assembled entirely on-orbit. This would forego the need to manufacture and manifest on a launch vehicle the 20 required small satellites, and instead require just one launch of the sensor stock. A graphical view of this use case is illustrated in Fig. 4.

2. Timeline and Concept of Operations

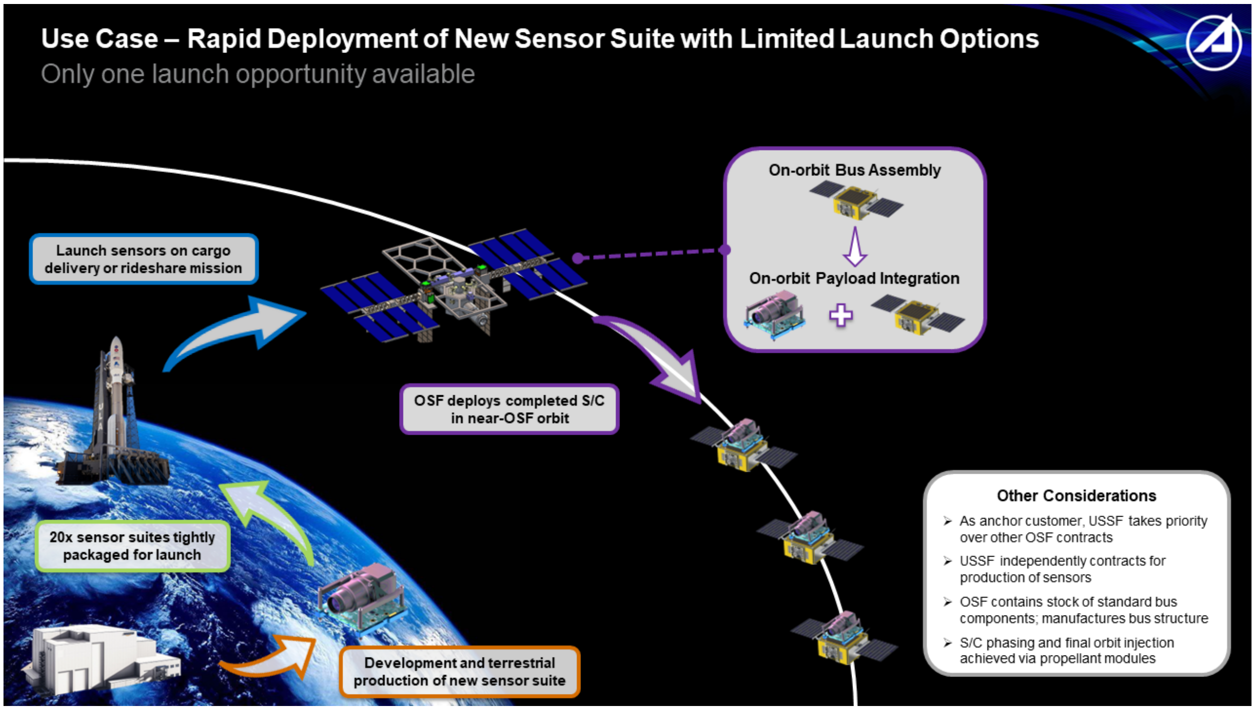
1) Customer solicits OSF operator to determine OSF availability over mission period.
2) Given criticality of customer mission, the OSF operator prioritizes this mission need and proceeds with initial planning.
3) Customer contracts suppliers for procurement of 20 Earth-manufactured sensor suites.
4) Customer contracts a launch vehicle and cargo provider to deliver the packaged batch of sensors to the OSF on-orbit.
5) OSF operator leverages the factory's maneuvering capability to place it in an orbit more favorable to deploy the satellites near their desired orbit.
6) OSF begins on-orbit manufacturing of satellite platform components (e.g., structural elements, radiators, panels) and integration with pre-made subsystem packages (e.g., power packs, communications suite, propulsion module).
7) Upon arrival of sensor suites, OSF integrates them onto mostly complete satellite platforms.
8) Upon completion of each satellite, on-orbit inspection and checkout are conducted.
9) OSF deploys completed and verified satellites into a near-OSF orbit.
10) Customer satellites employ pre-packaged "propulsion pack" to finalize placement into mission orbit and become operational.

C. Use Case 3: In-Space Depot of Common Replacement Units

Increasingly, space vehicles will be designed to be serviced on-orbit to extend mission life, upgrade operational capabilities, or pursue entirely new missions. This new vision for space operations requires various pieces of enabling infrastructure to be emplaced. Infrastructure needs include:

1) Prepared Clients – space vehicles which have been intentionally designed to be serviced through inclusion of modular and accessible components, fiducials and RPO aides, etc.
2) Servicers – with a variety of capabilities to conduct orbital inspection, repairs, swapping out of components, etc. of their clients.
3) Orbital Depots – on-orbit warehouses of components or consumables which alleviate the burden on servicers to transport all of these elements.

The focus of this vignette is an orbital depot intended to store, and if necessary, manufacture orbital replacement units for common components known to fail on orbit. It would act as a supplier to servicer vehicles to avoid the need for them to transport complete stocks of these components, reducing mass and volume requirements for the servicer. This is a CONOPS distinct from servicing missions replacing exquisite or specialized components such as payloads or uncommonly failed elements – in these cases, the servicer would likely have to be launched with this payload already in stock, likely from a terrestrial manufacturing source.



Use Case – Rapid Deployment of New Sensor Suite with Limited Launch Options

Only one launch opportunity available

Launch sensors on cargo delivery or rideshare mission

On-orbit Bus Assembly

On-orbit Payload Integration

OSF deploys completed S/C in near-OSF orbit

20x sensor suites tightly packaged for launch

Development and terrestrial production of new sensor suite

Other Considerations

- As anchor customer, USSF takes priority over other OSF contracts
- USSF independently contracts for production of sensors
- OSF contains stock of standard bus components; manufactures bus structure
- S/C phasing and final orbit injection achieved via propellant modules

Fig. 4 Use case concept of operations for rapid deployment of a new sensor suite.

1. Unique Offering of In-Space Manufacturing

A fundamental consideration for a future in-space servicing ecosystem is the logistics chain that gets components from where they are made to where they are needed. An orbital depot of common spacecraft components would be a key link in this chain. It would act as a supplier to servicer vehicles to avoid the need for them to be launched with stocks of these components. Decoupling the stock of the commodity from the servicer itself (while keeping the interfaces in mind) would reduce launch mass and volume requirements for the servicer, likely leading to reduced overall costs.

This approach makes for a responsive and sustainable servicing architecture where servicers can restock at the depot and continue supporting clients. The emphasis of this use case is on commonly failed components such as attitude actuators, common electronics, or power generation/storage devices. Where feasible, the orbital depot may manufacture and/or assemble parts of these components while cargo missions would supply the depot with bulk deliveries of pieces that cannot be feasibly manufactured on orbit.

2. Timeline and Concept of Operations

1) Orbital depot operator solicits industry to identify highest priority commonly failed components.
2) Operator engages with servicing community to identify which commonly failed components are suitable candidates for orbital servicing.
3) Operator / servicer/ client collaborate to implement modular designs and develop interface standards to ensure component compatibility.
4) Operator develops and deploys depot in location suitable for servicer and cargo delivery access.
5) (As necessary) Depot accepts cargo deliveries and conducts orbital manufacturing to build up stock of components available at the depot.
6) Based on client demand and servicing needs, servicer operators place orders for warehoused components to be picked up within some lead time.
7) Orbital depot prepares components (e.g., removal from stock, final assembly) for transfer to servicer.
8) Servicer vehicle approaches orbital depot and conducts RPO.
9) Orbital depot transfers prepared components package to servicer.
10) Servicer proceeds to client vehicle for servicing, orbital depot updates manifest, and logistics planners determine the need for further deliveries or orbital manufacturing of components.

D. Use Case 4: In-Space Manufacturing to Facilitate Servicing Architectures

Future outlooks of the in-space economy often skip the path between now and then. Yet, the interim period may serve as an area of opportunity for orbital manufacturing to provide a useful role. Prevalent in the ISAM startup community today are ideas related to RPO and servicing, including the design of docking interfaces and fiducial systems to facilitate autonomous operations. Legacy flight systems looking for improved capabilities provided by ISAM services may find benefit from modular fiducial systems rapidly manufactured on orbit. Integrated onto a vehicle on orbit, these fiducials could better facilitate a servicer's ability to dock with a legacy client. Additionally, bespoke grappling point hardware can be manufactured on orbit to mount onto older, larger vehicles to further facilitate these types of RPO and docking servicing activities.

1. Unique Offering of In-Space Manufacturing

There may be a unique opportunity for orbital manufacturing within this interim period that will consist of both unprepared, legacy spacecraft and future spacecraft which are better prepared for servicing. Commercial ISAM companies have developed creative ways to dock with legacy spacecraft (including the use of nozzles as grappling points), but these operations are time and resource intensive due to the unique nature of each legacy satellite. To better facilitate RPO and docking with unprepared spacecraft, orbital manufacturing could serve as the catalyst to quickly and effectively produce custom, mountable hardware. Within these possibilities, visual fiducial markers could be manufactured and later mounted onto legacy vehicles. While an initial, potentially time intensive, rendezvous would be needed to mount this hardware, it would enable future reoccurring servicing events to be conducted with greater ease. Simple grappling hardware could be manufactured on orbit and mounted on unprepared hardware to facilitate steadier and less risky operations with a lower chance of collision or improper docking.

The creation of fiducial markers and grappling hardware on orbit need not be limited to servicing cases, either. These parts could be manufactured directly as part of larger structures created on orbit to support assembly operations, simplifying the operations of vision systems and more easily guiding the work of assembly vehicles. With such features, assembly and rendezvous operations can be conducted with hardware that has been enhanced for such capabilities.

2. Timeline and Concept of Operations

1) Legacy (unprepared) spacecraft operator identifies that service is needed (either in near future or longer term).
2) Spacecraft operator contacts servicing operator.
3) Servicing operator solicits orbital manufacturing operator to manufacture necessary docking hardware.
4) Manufacturing operator develops and produces hardware for client.
5) Servicing operator retrieves manufactured hardware on orbit.
6) Servicing operator approaches client spacecraft and mounts fiducials and docking hardware.
7) Servicing operator utilizes RPO-friendly hardware to conduct repeated services, enabled and quickened by the implementation of orbitally-manufactured hardware .

IV. In-Space Manufacturing Key Technology Areas and Readiness Assessments

When considering the use cases just described, the 24 technologies identified for the smallsat factory are certainly still required for the broader manufacturing capability now envisioned. The use cases also highlight several technologies not included in that work. Figure 5 shows these additional areas. The technologies described for the smallsat factory are shown in white. The orange highlighted categories represent 15 new categories. Several of these are found in the two new groups: mobility and design for servicing and commonality. This section of the paper will describe these technologies and the state-of-the-art for each area. As in the previous paper, a maturity assessment is included for each technology using the scheme shown in Fig. 2.

A. Manufacturing

The first iteration of this roadmapping work focused on a narrow set of manufacturing capabilities needed to produce functional smallsats in space. Expanding the focus to include larger space vehicles, large structures, and persistent platforms means that a more diverse set of manufacturing techniques will likely be required.

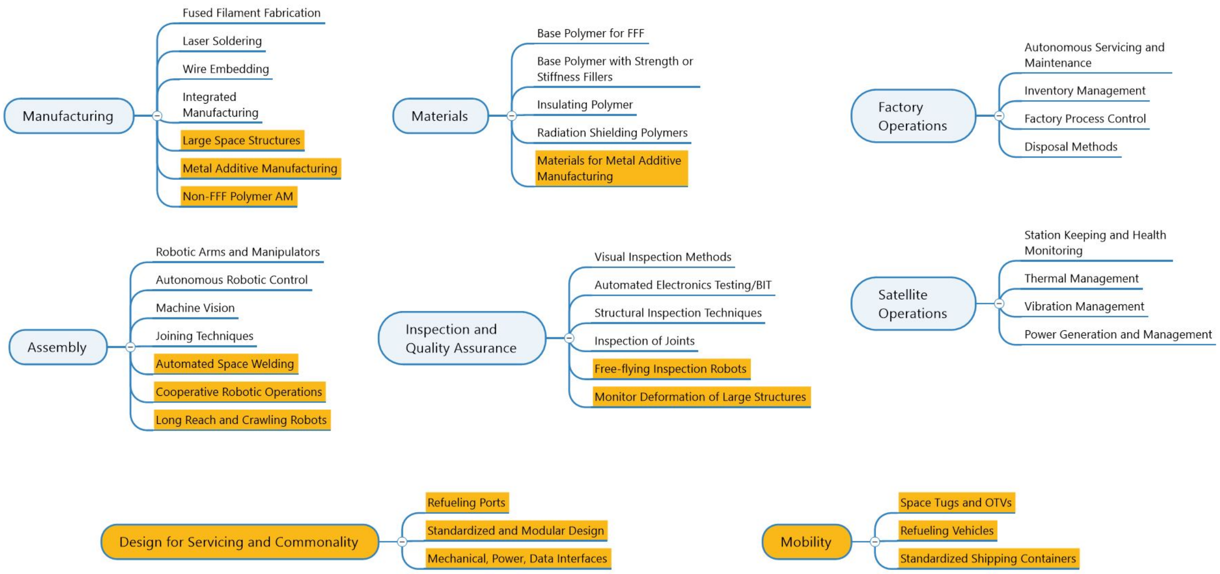


Fig. 5 Updated list of technology categories for a fully-capable on-orbit manufacturing system.

1. Non-FFF Polymer Additive Manufacturing - Maturity Level II

The only method of polymer AM demonstrated on the ISS so far is FFF, but there are other methods which may be valuable as the span of in-space manufacturing grows. Volumetric additive manufacturing (VAM) techniques are in development which allow parts to be manufactured without support material, and these techniques may allow for faster manufacturing than layer-based methods. Whyte et al. have reviewed several recent VAM efforts in their work [13]. One example of VAM, called computed axial lithography, has been demonstrated in parabolic flights as well as a sub-orbital mission on Virgin Galactic's Galactic 07 mission [14].

2. Metal Additive Manufacturing - Maturity Level II

It is likely that metal parts will be required for certain applications, and metal AM methods will offer a promising alternative to conventional subtractive techniques. Numerous other works have described the host of different metal AM techniques, and certainly some are more suited to the space environment than others [15, 16]. Printers using feedstock of metal powder encapsulated in a polymer matrix have shown potential to produce high-quality parts, and this technique was recently demonstrated in the first metal AM machine on the ISS, developed by Airbus for the European Space Agency [17, 18].

3. Manufacturing of Large Structures - Maturity Level I

While assembling large structures by connecting pre-fabricated parts is a viable strategy, several recent and continuing activities are exploring how to architect and build large space structures using in-space robotic assembly techniques. Hoyt et al. considered the value proposition and feasibility of making composite truss structures in space to produce large spacecraft structures including solar arrays and antennas. They developed the Trusselator device to form long lengths of composite truss [19]. NASA's Automated Reconfigurable Mission Adaptive Digital Assembly Systems (ARMADAS) project looks to autonomously assemble large structures from modular units called voxels. They have developed builder robots to work together [20, 21]. Chapin et al. from the Virginia Tech Field and Space Experimental Robotics (FASER) Laboratory have developed the Build On-orbit Robotically Assembled Gigatruss (BORG), which is a mixed assembly architecture that combines both deployable and strut assembled elements [22]. Wong et al. from NASA Langley Research Center (LaRC) described a distributed robotic system consisting of several different robotic manipulators that assembles and welds a truss made of free struts and joints [23].

B. Materials

1. Materials for Metal Additive Manufacturing - Maturity Level II

Diversifying the types of manufacturing activities available in space will also require using a wider array of materials. For instance, including metal additive manufacturing will require that the best options for feedstock are identified. A major need in this area will be standardized and widely available catalogs of the types of materials available for manufacturing. With the likelihood that multiple end users may use the same fabrication systems, an authoritative source of material properties and characteristics will be needed to allow for digital modeling of the proposed products.

C. Assembly

The robotic operations for the OSF concept depticted in Fig. 1 were simplified by a rotating hub to move the manufacturing stations to the product satellite's location. For the more complex products needed for the use cases in this paper, robotic operations will need to be more sophisticated.

1. Automated Space Welding - Maturity Level II

Another key area to be considered here is in-space welding, which may be required to join large portions of space structure together. Naden and Prater compiled a comprehensive review of welding technologies used in space in 2020 [24]. Sowards presented another review of the state-of-the art in this area and identified several possible examples of its use from a NASA perspective [25]. A notable reality for this area is the need to advance the level of automation in the processes, since a diversified manufacturing ecosystem that provides the required degree of responsiveness will not allow for human-in-the-loop operations in most cases. Successful welding techniques must be integrated with robotic systems to facilitate this level of automation.

2. Cooperative Robotic Operations - Maturity Level I

The complexity of structures to be manufactured and assembled in the fully-capable ecosystem will drive robotic operations that are cooperative in nature, where more than one manipulator will be conducting operations on a component at the same time. These operations will need to be controlled in a manner that minimizes conflicts and allows the synergistic effects of the operations to successfully develop an end product. Cooper et al. designed a reconfigurable modular robotic system based on the stacking of several Stewart platforms [26]. While this work focused on the needs from assembly on the lunar surface, the concept could have applications for on-orbit assembly as well.

3. Long-Reach and Crawling Robots - Maturity Level I

The need to assemble large structures drives the need for robotic operations capable of moving along a developing structure. For example, Nair et al. have proposed a dexterous walking robotic system with the 25m Large Aperture Space Telescope as the prospective use case [27]. A similar study from Nanjangud et al. considered five different robotic architectures to assemble the primary mirror for this telescope, and they ultimately proposed an end-over-end walking robot as the most appropriate solution [28]. The scale of structures assembled in space will also require robotic operations with the ability to reach more distant objects than currently possible. The NASA TALISMAN effort is one example of research going down this path [29].

D. Inspection and Quality Assurance

Expanding the in-space manufacturing scope beyond smallsats introduces new considerations to the challenge of performing inspections of existing systems and ensuring that manufacturing and assembly operations are conducted successfully.

1. Free-flying Inspection Robots - Maturity Level II

From a servicing perspective, vehicles with the ability to inspect existing satellites to find flaws, failures, and damage will be critical to ensuring resilient sensor networks are maintained. For proliferated systems, gaining knowledge of the need to replace an asset before the asset fails reduces the chance of system degradation. Servicers need non-destructive inspection systems to make this possible. Free-flying inspection robots will provide a way to augment other servicing and manufacturing assets, especially as the satellites and structures of interest get larger. While visual inspection techniques are proven, the additional need here is for the free flyers to work in cooperation with the host manufacturing system, augmenting its own ability to monitor progress along an operation. One recent example building toward this capability is the Astrobee system recently used on the ISS [30].

2. Monitoring Deformation of Large Structures - Maturity Level I

A new challenge stemming from the construction of larger space structures is the need to monitor their deformation during and after manufacturing operations. A major advantage of building these structures in orbit is the ability to reduce material, since launch loads are no longer a factor. A possible downside to this is a loss of geometric stiffness that allows for more compliance. There is likely much to learn from the civil engineering community, where monitoring the condition of large structures is commonplace. Existing techniques need to be adapted for the in-space manufacturing application and proven in relevant environments.

E. Design for Servicing and Commonality

The use cases described this paper drive the need to change the way the community designs and builds space vehicles. Future concepts should assume that servicing and upgrade are not only possible, but required to fully employ the systems.

1. Refueling Ports - Maturity Level III

As the desire for systems to maneuver without regret increases, all future satellite designs should include accessible, standardized refueling ports. While some current demonstrations propose cutting through insulation and other materials to reach existing ports, that should be seen as a means to and end. Previous work by NASA during the Robotic Refueling Mission showed the feasibility to transfer fuel in orbit [31]. Notable efforts to design refueling ports for satellites have gained momentum in the last few years. Orbit Fab has developed the Rapidly Attachable Fluid Transfer Interface (RAFTI), based on technology demonstrated on the ISS in 2019 [32, 33]. RAFTI has been accepted as a standard interface by the USSF Space Systems Command (SSC) and will be demonstrated in several future missions. Northrop Grumman has also developed a refueling port, the Passive Refueling Module (PRM). It has also been designated as a favored interface by SSC [34].

2. Standardized and Modular Design - Maturity Level I

A second key area to be advanced is the architecture of satellites. Lessons can be learned from the aircraft world, where many avionics systems are designed as line replaceable units (LRU). This LRUs can be swapped as required with little to no effect on the rest of the system. Space vehicles can be designed in a similar fashion, where key parts of major subsystems can be removed and replaced as needed. While the current satellite constellations have exceeded life expectations in many cases, the ability to refuel future vehicles will certainly expose users to higher rates of component failures. Early works including Reynerson's Spacecraft Modular Architecture Design and the SpaceFrame concept from Miller et al. showed the potential benefits of modular design [35, 36]. Hu et al. provide a good overview of more recent efforts to design self-reconfigurable spacecraft, which depend on the modularity envisioned in this work [37]. The SCHUMANN project, a Horizon Europe research initiative, is another example of this line of work [38, 39].

3. Mechanical, Power, and Data Interfaces - Maturity Level III

Common interface standards defining how components connect to other components and how servicer vehicles interact with other vehicles are essential to making space capabilities as resilient as possible. One example of early work in this area is the interface designed for the MIT SWARM spacecraft test bed [40]. A more recent example is the iBOSS Intelligent Space System Interface (iSSI), which provides mechanical, power, data, and thermal interfaces [41, 42]. The iSSI can be configured in several ways to meet interface requirements, and it is available as both an active and passive version. Voyager Space has also made significant progress in this area, with three major projects in development based on electropermanent magnets [43]. The DogTag is a mechanical interface allowing a satellite to be grappled in a variety of ways. The MagTag is a latching connector to facilitate repairs, upgrades, or installation of other payloads. The Voyager Space Docking, Anchoring, and Towing Universal Match Plate (DATUM) will provide a scalable interface that allows for large amounts of initial misalignment between components. A third example of recent work in the interface area is the Lockheed Mission Augmentation Port (MAP) standard, which the company used to design its own Augmentation System Port Interface (ASPIN) [44, 45]. The MAP is envisioned to facilitate upgrades to existing hardware to extend mission life.

F. Mobility

The final technologies considered for this iteration of the roadmap are those that facilitate the mobility of materials and end products throughout the manufacturing ecosystem and end use environment.

1. Space Tugs and Orbital Transfer Vehicles (OTVs) - Maturity Level III

Several previous and ongoing ventures have advanced concepts for space tugs or orbital transfer vehicles. As previously mentioned, Northrop Grumman successfully completed docking of its Mission Extension Vehicle (MEV-2) with the Intelsat 10-02 in April of 2021 after successfully docking the MEV-1 with Intelsat 901 in February of the previous year. Firefly Aerospace recently acquired Spaceflight Inc. and continues to advance the Sherpa tug, while also introducing plans for a line of scalable orbital vehicles named Elytra. The Elytra was recently chosen as the subject of a trade study to understand Firefly's capabilities to rapidly launch vehicles for the Defense Innovation Unit [46]. Astroscale has developed its own LEXI vehicle to extend the life of existing satellites and if needed, redeploy to new orbits. Starfish Space is developing the Otter servicing vehicle through a USSF Strategic Funding Increase (STRATFI) agreement to provide augmented maneuver to existing vehicles [47, 48]. To this point, the focus on orbital transfer vehicles has been extend service life or relocation existing assets. However, these technologies can be expanded to also move the raw materials needed to maintain a robust in-space manufacturing system.

2. Refueling Vehicles - Maturity Level III

The value of in-space manufacturing capabilities will be greatly magnified if the manufacturing sites and the resulting products can be refueled. The Orbital Express mission demonstrated in 2007 that hydrazine could be transferred from one vehicle to another, but work slowed on the refueling front until the past few years. Several upcoming efforts are now seeking to develop refueling vehicles and demonstrate refueling operations in-orbit, which should result in the community matching and surpassing what Orbital Express accomplished. Orbit Fab launched its Tanker-001 Tenzing in 2021, a 35 kg satellite which stored high test peroxide for use by other future spacecraft [49]. The USSF selected Orion Space Solutions and its partners to execute the Tetra-5 mission, which will demonstrate RPO and docking using multiple spacecraft in geostationary orbit. The project completed critical design review in January 2024 [50–52]. In another ongoing project, Astroscale is developing the Astroscale Prototype Servicer for Refueling (APS-R) as part of a USSF contract to advance refueling technology. It will demonstrate refueling with a prepared vehicle as well as rendezvous and docking with a fuel depot [6, 53, 54].

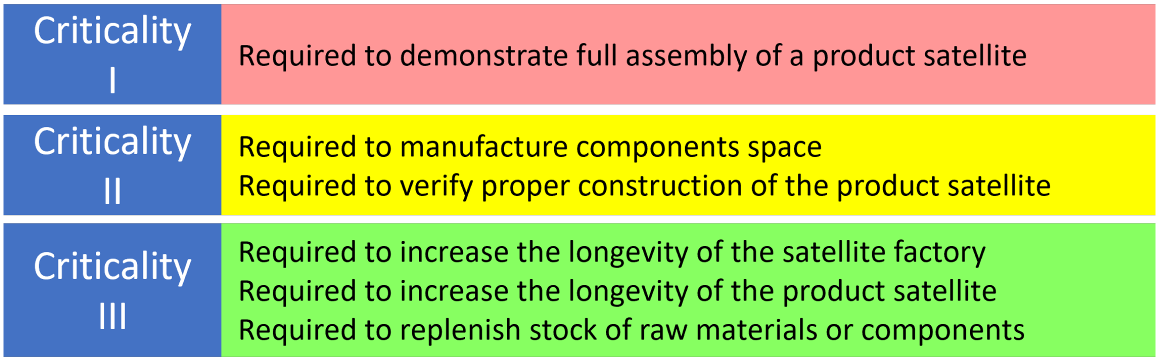
3. Standardized Shipping Containers - Maturity Level I

Another mobility-related need is to standardize how raw materials are moved from launch to their final destination. Terrestrial logistics systems have shown the benefit of having standardized shipping containers that allow for variety in the items shipped while allowing the overall system to use standard operating procedures. A standardized container for moving raw materials and terrestrially-assembled modules would facilitate similar process standardization in the on-orbit servicing and manufacturing ecosystem. Currently, several resupply vehicles for the ISS such as SpaceX Dragon, the Northrop Grumman Cygnus, and the Russian Progress provide a baseline, but further work is required to produce a completely standardized container suited for ISAM purposes [55–57].

V. Updated Maturity and Criticality Matrix

The previous Maturity and Criticality Matrix was updated to include the 15 additional technology areas identified in this paper. The method used to assess maturity did not change from that used in the previous work. The criticality assessment was changed slightly to account for the addition of mobility and logistics considerations to this study, and the updated definitions are shown in Fig. 6. The updated matrix including all 39 relevant technologies is shown in Fig. 7.

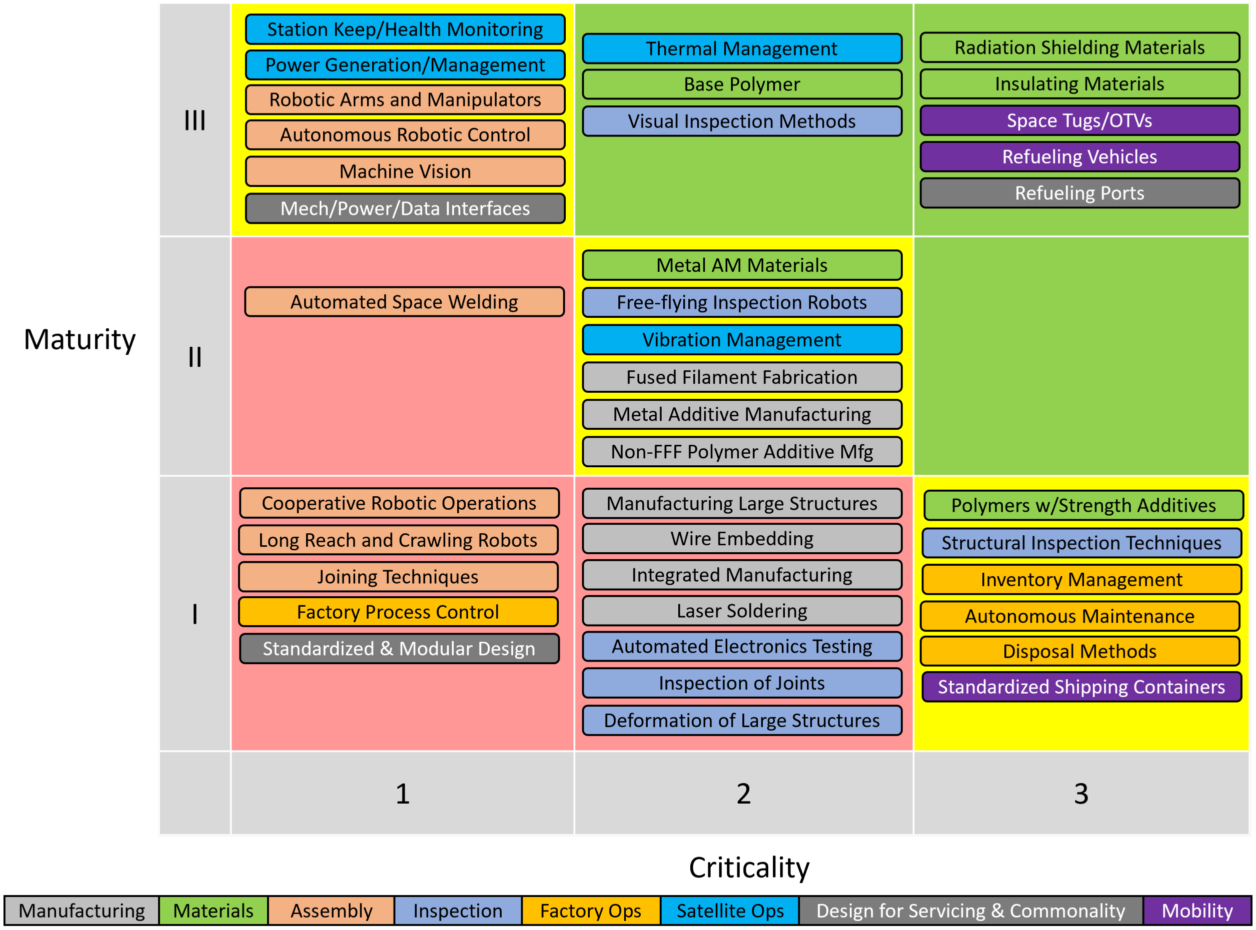
The maturity assessments for three categories have been updated since the previous paper. First, the assessment for laser soldering has been lowered from Maturity II to Maturity I. As noted in the previous paper, some microgravity experiments on the ISS have shown the potential for soldering to work in the general space environment. Further consideration of these experiments showed that they were entirely manual in nature. Given that any laser soldering used



Criticality I	Required to demonstrate full assembly of a product satellite
Criticality II	Required to manufacture components space Required to verify proper construction of the product satellite
Criticality III	Required to increase the longevity of the satellite factory Required to increase the longevity of the product satellite Required to replenish stock of raw materials or components

Fig. 6 Technology criticality levels.

for in-space manufacturing will need to be almost completely automated, it is appropriate to reclassify this technology as Maturity I until automated procedures are demonstrated in a relevant environment. On the other hand, Visual Inspection was reclassified from Maturity I to Maturity III. The original assessment did not take into account several initiatives to inspect existing space space vehicles using visual means, such as ADRAS-J, The Aerospace Corporation AeroCube, the Northrop-Grumman Space Logistics MRV, and the NASA Visual Inspection Poseable Invertebrate Robot (VIPIR). While these efforts focused on whole-vehicle inspection, they indicate that visual inspection methods are a viable means



Maturity

III	Station Keep/Health Monitoring Power Generation/Management Robotic Arms and Manipulators Autonomous Robotic Control Machine Vision Mech/Power/Data Interfaces	Thermal Management Base Polymer Visual Inspection Methods	Radiation Shielding Materials Insulating Materials Space Tugs/OTVs Refueling Vehicles Refueling Ports
II	Automated Space Welding	Metal AM Materials Free-flying Inspection Robots Vibration Management Fused Filament Fabrication Metal Additive Manufacturing Non-FFF Polymer Additive Mfg	
I	Cooperative Robotic Operations Long Reach and Crawling Robots Joining Techniques Factory Process Control Standardized & Modular Design	Manufacturing Large Structures Wire Embedding Integrated Manufacturing Laser Soldering Automated Electronics Testing Inspection of Joints Deformation of Large Structures	Polymers w/Strength Additives Structural Inspection Techniques Inventory Management Autonomous Maintenance Disposal Methods Standardized Shipping Containers
	1	2	3

Criticality

Manufacturing	Materials	Assembly	Inspection	Factory Ops	Satellite Ops	Design for Servicing & Commonality	Mobility

Fig. 7 Maturity and criticality matrix for in-space manufacturing technologies.

to track progress as products are manufactured and assembled in space.

As in the previous version of this work, the technologies in the lower left (red) blocks (low maturity and medium/high criticality) should generally have the highest priority. They are on the critical path to achieving the in-space manufacturing ecosystem envisioned in this paper, and they have not been demonstrated in environments relevant to the goal. Technologies in the upper right corner (green) are those that need the least amount of near-term effort. While advancements are still valuable for these areas, they will likely be at the maturity needed given current and planned work.

VI. Relationships with NASA Technology Shortfalls

It is useful to view the technology needs identified in this paper alongside other efforts which have worked to identify gaps in the current state-of-the-art. One such source is NASA's shortfall list. In spring 2024, the NASA Space Technology Mission Directorate (STMD) released a list of 187 technology shortfalls to describe areas needing development in support of future science and exploration missions. Members of the aerospace community were asked to rate the importance of these shortfall areas, and STMD released the results of the ranking process in July 2024. When comparing the list of NASA shortfalls to the technology areas described in this roadmap, there is considerable overlap. Among the 187 identified shortfalls, 34 have direct applicability to the technology areas identified in this roadmap. A mapping of these NASA shortfalls to the technology areas identified in this paper is shown in Fig. 8. Table 1 shows a list of the 34 NASA shortfalls along with three of the ranking categories from the NASA report. On average, the in-space manufacturing focused shortfalls applicable to this paper were ranked higher in the large industry category than in the NASA centers ranking or the overall integrated ranking. [58].

VII. Advancing the Maturity of Key Technologies

The maturity assessments in the previous Orbital Smallsat Factory paper revealed the need to expand opportunities for in-space experiments, tests, and demonstrations that advance the readiness of required technologies. As the focus expands to the entire in-space manufacturing ecosystem, this need becomes even larger. The results of the maturity assessments conducted for this work and the previous paper show that almost half the relevant technologies are either in the Maturity I category, meaning that there is still work remaining to prepare them for an in-space evaluation, or developers are awaiting an opportunity to conduct an experiment or demonstration on-orbit. The cost and time to develop bespoke space vehicles to host experiments are prohibitive for many players in the ISAM community. Previously, options for in-space experiments and demonstrations were concentrated to a few major pathways, but new avenues continue to proliferate. The final section of this paper highlights the existing and emerging pathways to make these activities happen.

1. Parabolic Flights

For cases where short durations of simulated microgravity are sufficient for the experiment, parabolic flights continue to be an option. NASA currently contracts with Zero Gravity Corporation to provide these services [59, 60]. Novespace also conducts parabolic flights for a variety of Europe-based entities [61].

2. The International Space Station

The ISS provides many options for microgravity experiments both inside and outside the pressurized environment. The NASA Researcher's Guide to ISS Technology Demonstration is a thorough resource describing the various technology demonstration programs as well as the internal and external accommodations on the ISS [62, 63]. Opportunities to propose experiments and demonstrations to be performed on the ISS are described in National Lab Research Announcements, which are released on a regular basis. Previous opportunities can be viewed at the ISS National Laboratory website [64].

3. The Space Test Program

The Space Test Program (STP) provides another mechanism to demonstrate technologies with clear military utility. Since its first launch in 1967, STP has executed over 300 missions to provide space access to experimental payloads [65]. Braun et al. provide a detailed description of the Space Experiments Review Board (SERB) process used to review and select potential payloads [66]. Going forward, STP plans to leverage commercially developed space vehicles to host

Manufacturing

1408: Advanced deployable load-bearing structures
1485: In-Space and On-Surface Manufacturing of Parts/Products from Surface and Terrestrial Feedstocks
1491: Additive Manufacturing of Large-Scale Components
1495: Advanced Manufacturing for Improved Dimensional Control of Large-Scale Space Structures
1496: In-Space and On-Surface Manufacturing, Assembly, and Repair of Composite Structures
1576: Micrometeoroid-Robust Protection of In-space Observatories

Materials

1490: Additive Manufacturing for New and High-Performance Materials

Assembly

379: Upgrade or Install Instruments on Large Space Observatories
498: Broad and dependable supply chain for space-qualified robotic hardware, electronics, and associated software
680: Robust Robotic Intelligence for High-Tempo Autonomous Operations in Dynamic Mission Conditions
1432: Rendezvous, Proximity Operations, and Debris Remediation using Small Spacecraft
1487: In-Space and On-Surface Welding Technologies for Manufacturing, Assembly, and Construction
1538: General-Purpose Robotic Manipulation to Perform Human-Scale Logistics, Maintenance, Outfitting, and Utilization
1540: Intelligent Robots for the Servicing, Assembly, and Outfitting of In-Space Assets and Industrial-Scale Surface Infrastructure
1542: Metrics and Processes for Establishing Trust and Certifying the Trustworthiness of Autonomous Systems
1543: Multi-Agent Robotic Coordination and Interoperability for Cooperative Task Planning and Performance
1544: Resilient Agency: Adaptable Intelligence and Robust Online Learning for Long-Duration and Dynamic Missions
1545: Robotic Actuation, Subsystem Components, and System Architectures for Long-Duration and Extreme Environment Operation
1548: Sensing for Autonomous Robotic Operations in Challenging Environmental Conditions
1554: High Performance Onboard Computing to Enable Increasingly Complex Operations

Inspection

1486: In-Space and On-Surface NDE and Qualification of Components for Manufacturing, Assembly, and Construction
1549: Advanced Data Acquisition Systems for Diverse Applications
1625: Intelligent Multi-Agent Constellations for Cooperative Operations
1483: Enable commercially-provided Rendezvous, Proximity Operations, and Capture (RPOC) products and services
1537: Free-Flying Systems for Robotic Inspection, Data Collection, and Servicing of In-Space Assets

Factory Operations

1477: Mitigation of New Orbital Debris Generation
1494: Digital Transformation Technologies for Terrestrial ,In-Space, On-Surface Manufacturing, and Operations
1534: Autonomous Robotics for Sustained In-Space Manufacturing Operations

Satellite Operations

1535: Autonomous Vehicle, System, Habitat, and Infrastructure Health Monitoring and Management
1575: Thermal and Vibrational Isolation for Ultra-stable Science Payloads

Design for Servicing and Commonality

376: Modular design for in-space installation
512: Cooperative interfaces, aids, and standards
513: Robotic Assembly and Construction of Modular Systems for Sustained In-Space Infrastructure

Mobility

1431: Access Beyond LEO for Small Spacecraft

Fig. 8 In-space manufacturing relevant NASA shortfalls grouped into technology categories.

Table 1 In-space manufacturing relevant NASA shortfalls with priority ranking [58].

ID	Name (Abbreviated)	Integrated Ranking	NASA Centers	Large Industry
379	Upgrade or Install Instruments on Large Space Observatories	125	137	113
376	Modular design for in-space installation	109	101	82
498	Broad and dependable supply chain for space-qualified robotic hardware	40	152	19
512	Cooperative interfaces, aids, and standards	101	75	57
513	Robotic Assembly and Construction of Modular Systems for Sustained In-Space Infrastructure	153	100	80
680	Robust Robotic Intelligence for High-Tempo Autonomous Operations	85	67	95
1408	Advanced deployable load-bearing structures	150	117	106
1431	Access Beyond LEO for Small Spacecraft	69	43	89
1432	Rendezvous, Proximity Operations, and Debris Remediation using Small Spacecraft	93	90	63
1477	Mitigation of New Orbital Debris Generation	95	7	13
1483	Enable commercially-provided Rendezvous, Proximity Operations, and Capture	78	168	34
1485	In-Space and On-Surface Manufacturing of Parts/Products from Surface and Terrestrial Feedstocks	92	70	43
1486	In-Space and On-Surface NDE and Qualification of Components	116	116	134
1487	In-Space and On-Surface Welding Technologies for Manufacturing, Assembly, and Construction	179	108	110
1490	Additive Manufacturing for New and High-Performance Materials	149	48	16
1491	Additive Manufacturing of Large-Scale Components	154	55	67
1494	Digital Transformation Technologies for Terrestrial, In-Space, On-Surface Manufacturing	176	128	133
1495	Advanced Manufacturing for Improved Dimensional Control of Large-Scale Space Structures	171	156	97
1496	In-Space and On-Surface Manufacturing, Assembly, and Repair of Composite Structures	174	139	129
1534	Autonomous Robotics for Sustained In-Space Manufacturing Operations	166	132	42
1535	Autonomous Vehicle, System, Habitat, and Infrastructure Health Monitoring and Management	72	72	79
1537	Free-Flying Systems for Robotic Inspection, Data Collection, and Servicing of In-Space Assets	155	163	120
1538	General-Purpose Robotic Manipulation to Perform Human-Scale Logistics	65	112	31
1540	Intelligent Robots for the Servicing, Assembly, and Outfitting of In-Space Assets	133	77	51
1542	Metrics and Processes for Establishing Trust of Autonomous Systems	33	58	52
1543	Multi-Agent Robotic Coordination for Cooperative Task Planning and Performance	139	85	86
1544	Resilient Agency: Adaptable Intelligence for Long-Duration and Dynamic Missions	177	122	167
1545	Robotic Actuation for Long-Duration and Extreme Environment Operation	5	40	28
1548	Sensing for Autonomous Robotic Operations in Challenging Environmental Conditions	18	44	26
1549	Advanced Data Acquisition Systems for Diverse Applications	151	171	145
1554	High Performance Onboard Computing to Enable Increasingly Complex Operations	3	3	21
1575	Thermal and Vibrational Isolation for Ultra-stable Science Payloads	88	174	101
1576	Micrometeoroid-Robust Protection of In-space Observatories	81	155	107
1625	Intelligent Multi-Agent Constellations for Cooperative Operations	80	166	165
	Average Ranking	106.6	102.3	78.7

payloads through the STEP 2.0 contract, which will provide rapid access to space using a range of platforms [67].

4. Commerical Rideshare Missions

Rideshare opportunities have also emerged as an option to showcase developing technologies in relevant environments. The SpaceX Transporter-5 mission was a good example of this, with multiple ISAM-relevant demonstrations on board [68]. Nanoracks operated a hosted payload on the upper stage which completed the first ever demonstration of metal cutting in space [69, 70]. Also included in this mission were several orbital transfer vehicles.

5. NASA Flight Opportunities Program

The NASA Flight Opportunities Program provides access to several types of flight tests to mature capabilities for NASA missions and commercial applications. Notably, NASA awarded new 15 new contracts in March 2024 for commercial flight providers. Eight of these contracts were for spacecraft or launch vehicle stages that will host payloads for at least one orbit while providing power and communications capabilities for the hosted payloads [71, 72].

6. *Persistent Platforms*

While the current methodologies will continue to be needed, expanding the availability of persistent testbeds which can host experiments is crucial to making in-space manufacturing a reality. Plotke et al. have described a persistent platform called the Advanced Space-Based Testbed (XST) to realize the USSF concept of In-Space Developmental Test (iSDT) [73]. On the commercial side, Arkisys is developing its Port concept, which will provide partners with a fully-robotic destination to host new payloads and technologies [74, 75].

VIII. Conclusion

This paper expanded on previous work to describe the full set of technologies required to realize an in-space manufacturing ecosystem. Four prospective use-cases were described that show the variety of ways in-space manufacturing will benefit customers and providers of space capability. In total, 39 separate technologies have been evaluated based on their technical maturity and their importance to establishing an initial operational capability for a satellite factory supported by a full logistics system. This work illustrates the breadth of activities required to make in-space manufacturing a reality, and it provides a novel assessment to help interested parties prioritize current and future development efforts.

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