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ON-ORBIT SERVICING,
ASSEMBLY, AND
MANUFACTURING

On-orbit Servicing, Assembly, and Manufacturing (OSAM) State of Play

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2021 Edition

A document from the OSAM National Initiative to characterize the current state of OSAM capabilities.

EXECUTIVE SUMMARY

The future of spaceflight will yield increasingly more ambitious missions to support civil, national security, and commercial space sectors. Achieving these ambitious missions is not feasible using the traditional paradigm of launching an integrated, fully functioning system on a single launch vehicle. For example, science and human exploration missions will require spacecraft larger than any foreseeable launch vehicle fairing, national security missions will require persistent assets that are mobile and resilient, and commercial space missions will require cost-effective ways to update to the latest technology on orbit.

On-orbit Servicing, Assembly, and Manufacturing (OSAM) can vastly expand the performance, availability, resilience, and lifetime of space systems compared to the traditional paradigm. Fostering an ecosystem that leverages OSAM capabilities changes the space operations paradigm, creating the foundation for sustainable operations and serving as a multiplier for other capabilities like space logistics, power generation, and reusability.

Previous achievements in OSAM have enabled ambitious human and robotic space missions. The International Space Station (ISS), the Hubble Space Telescope, and the Mission Extension Vehicle demonstrate the dramatic operational missions that can be achieved using OSAM capabilities. Many current flight demonstrations are advancing areas that will enable the next generation of civil, national security, and commercial space missions.

This document describes the current state of OSAM missions, capabilities, and developments. Compiling and organizing the available OSAM capabilities will help mission designers incorporate OSAM technologies into their concepts, create the starting point for technology development plans and roadmaps, and provide technologists a survey of the field they are developing. This document divides the OSAM capabilities into 11 capability areas that describe the functions or activities that would be performed in space using OSAM.

- **Robotic Manipulation**: Robotic manipulators have flown on a variety of missions, from surface robotics to long reach manipulation on ISS. Many are being developed to increase autonomy, reduce cost, and proliferate the use of space robotics.
- **Rendezvous & Proximity Operations (RPO), Capture, Docking, and Mating**: this capability is the first step in an OSAM mission and has been included in space flight since Gemini VIII in 1966. Advancements in autonomy, formation flying, standardization/interoperability, and mating operations will make future OSAM missions more commonplace.
- **Relocation**: Moving spacecraft with a servicing vehicle or tug presents a large opportunity for sustainable space operations such as mission extension, debris removal, and maneuverability. After the first commercial relocation mission in 2019 and a second in 2021, many activities in this capability area are looking to become operational soon.
- **Planned Repair, Upgrade, Maintenance, and Installation**: Planned servicing is the center of an OSAM ecosystem where the client vehicle and OSAM servicing agents are co-designed to operate

together. Modular interfaces are being developed to support multiple types of spacecraft in this ecosystem to provide mechanical, fluid, power, data, and thermal connections.

- **Unplanned or Legacy Repair and Maintenance**: Providing refueling, modular repair and/or replacement, and augmentation to a legacy client spacecraft that is not prepared to receive those services is a valuable service. Activities to develop mission-specific functionality are important for missions like debris removal, scavenging, and manipulating non-cooperative spacecraft.
- **Refueling and Fluid Transfer**: Storable fluid transfer has been demonstrated many times, including in operational missions like the ISS. The future is heading toward commercial refueling services (especially for storable fluids) and demonstrations are planned to test large-scale cryogenic fluid transfer in space.
- **Structural Manufacturing and Assembly**: The technologies which enable creating or assembling structures in space to create spacecraft components or subsystems are wide ranging. Historically focused on astronaut assembly, the current advancements in this capability area emphasize autonomous, robotic manufacturing and assembly.
- **Recycling, Reuse, & Repurposing**: Recycling, reuse, and repurposing include spacecraft components and materials as part of the “native” resources available for sustained presence. The eventual future in this capability area is in expanding the materials that can be reused, tailoring the performance of those materials, and understanding the mission implications of this capability.
- **Parts and Goods Manufacturing**: The initial capability for parts and good manufacturing in space focused on the use of 3D printed plastics. Production techniques currently in development aim to expand the production capabilities to metals, electronics, and in-situ regolith infused materials.
- **Surface Construction**: The scope of structures to be built on a planetary surface spans all aspects of surface infrastructure, including horizontal (landing pads, roads, etc.) and vertical (power, habitation, etc.) construction. Advancements in surface construction address needs for excavating, constructing, and outfitting infrastructure on a planetary surface.
- **Inspection and Metrology:** Inspection and metrology are needed to survey and analyze a spacecraft’s configuration, size, shape, state of repair, or other features of interest. The systems to perform this task Include free-flyer inspection, non-destructive evaluation, close (robotic) inspection, and visual or multispectral inspection.

The *OSAM State of Play* is the first step in a journey to encourage the use of OSAM capabilities in space. Compiling and organizing the current state of OSAM provides a simple resource for those working in the OSAM ecosystem to ensure that the advancements being made build upon the investments of the past. The state of play is ever changing as new capabilities are developed, and this document will be periodically updated to ensure that it is relevant to those who need it in the future.

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TABLE OF ACRONYMS

AC-10	Aerocube-10
Access	Assembly Concept for Erectable Space Structures
ACME	Additive Construction with Mobile Emplacement
AFRL	Air Force Research Laboratory
AgMan	Agile Manufacturing for Space Systems
AMF	Additive Manufacturing Facility
AMS	Alpha Magnetic Spectrometer
ANGELS	Automated Navigation and Guidance Experiment for Local Space
ARMADAS	Automated Reconfigurable Mission Adaptive Digital Assembly Systems
BONSAI	Bus-Replica for On-Orbit Systems via Advanced Integration
CAVE	Collaborative Autonomous Vehicle Environment
CHAPEA	Crew Health and Performance Analog
CNC	Computerized Numerical Control
DARPA	Defense Advanced Research Projects Agency
DeSeL	Deployable Structures Lab
Dextre	Special Purpose Dexterous Manipulator
EASE	Experimental Assembly of Structures in EVA
EBW	Electron Beam Welding
EELV	Evolved Expendable Launch Vehicle
ELSA-d	End-of-Life Services by Astroscale Demo
ESPA	EELV Secondary Payload Adapter
ETS	Engineering Test Satellite
EVA	Extravehicular Activity
EXPRESS	Xpedite The PRocessing of Experiments to Space Station
FARE	Fluid Acquisition and Resupply Experiment
FASER	Field and Space Experimental Robotics
FDM	Fused Deposition Modeling
FREND	Front-end Robotics Enabling Near-term Demonstration
GaLORE	Gaseous Lunar Oxygen from Regolith Electrolysis
GEO	Geostationary Orbit
GOLD	General Purpose Latching Device
HST	Hubble Space Telescope
HTP	High-Test Peroxide
ISA	In-Space Assembly
ISAAC	Integrated System for Autonomous and Adaptive Caretaking
ISFR	In-Situ Fabrication and Repair
ISM	In-Space Manufacturing
ISRU	In-situ Resource Utilization
ISS	International Space Station
Issl	Intelligent Space System Interface
JEM-EF	Japanese Experiment Module – Exposed Facility
JEM-RMS	Japanese Experiment Module Remote Manipulator System
LANCE	Lunar Attachment Node for Construction and Excavation
LEO	Low-Earth Orbit
LH2	Liquid Hydrogen
LINCS	Local Intelligent Networked Collaborative Systems
LOX	Liquid Oxygen

LSMS	Lightweight Surface Manipulation System
MAMBA	Metal Advanced Manufacturing Bot-Assisted Assembly
MER	Mars Exploration Rover
MEV	Mission Extension Vehicle
MMPACT	Moon-To-Mars Planetary Autonomous Construction Technology
MSG	Microgravity Science Glovebox
MVACS	Mars Volatiles and Climate Surveyor Robotic Arm
NASA	National Aeronautics and Space Administration
NCST	Naval Center for Space Technology
Ninjar	NASA Intelligent Jigging and Assembly Robot
NTO	Nitrogen Tetroxide
OMV	Orbital Maneuvering Vehicle
ORS	Orbital Refueling System
OSAM	On-orbit Servicing, Assembly, and Manufacturing
PASS	Precision Assembled Space Structures
PAUT	Phased Array Ultrasonic Test
RASSOR	Regolith Advanced Surface Systems Operations Robot
REACT	Relevant Environment Additive Construction Technology
RELL	Robotic External Leak Locator
RPO	Rendezvous and Proximity Operations
RRM3	The Robotic Refueling Mission 3
RRP	Redwire Regolith Print
RSGS	Robotic Servicing of Geosynchronous Satellites
Samurai	Strut Assembly, Manufacturing, Utility, and Robotic Aid
SCOUT	SpaceCraft Observe and Understand Things
SEEKER	Space Environmental Effects
SFA	JAXA Small Fine Arm
SFMD	Storable Fluid Management Demonstration
SHA	Sample Handling Assembly
SHEARLESS	Sheath-based Rollable Lenticular-Shaped and Low-Stiction Composite Booms
SHOOT	Superfluid Helium On-Orbit Transfer
SIMPLE	Sintered Inductive Metal Printer with Laser Exposure
SIROM	Standard Interface for Robotic Manipulation of Payloads
SLAB	Space Rendezvous Laboratory
SPHERES	Synchronized Position Hold Engage and Reorient Experimental Satellite
SPIDER	Space Infrastructure Dexterous Robot
SRL	Space Robotics Laboratory
SRMS	Shuttle Remote Manipulator System
SSRMS	Space State Remote Manipulator System
STMD	Space Technology Mission Directorate
STS	Space Transportation System
SUV	Space Utility Vehicle
TALISMAN	Tendon-Actuated Lightweight In-Space MANipulator
TDM	Technology Demonstration Mission
UDMH	Unsymmetrical Dimethlyhydrazine
VIPIR	Visual Inspection Poseable Invertebrate Robot
xGEO	Cislunar Orbital Regime (beyond GEO)
XSS	Experimental Satellite System

1 INTRODUCTION

Historically, spacecraft are constructed on Earth and launched as an integrated, fully functioning system on a single launch vehicle. This approach constrains the size, volume, mass, and mission design of those systems, as they must fit within the given launch vehicle fairing. Additionally, the operational life of the system is indirectly limited due to an inability to perform servicing, repairs, or upgrades after deployment.

The future of spaceflight will yield increasingly more ambitious missions to support civil, national security, and commercial space sectors. Achieving these ambitious missions is not feasible using the traditional paradigm. For example, science and human exploration missions will desire payloads that are larger than any foreseeable launch vehicle fairing, national security missions will require persistent assets that are mobile and resilient, and commercial space missions will require cost-effective ways to update to the latest technology on orbit.

On-orbit Servicing, Assembly, and Manufacturing (OSAM) is an emerging set of capabilities that enables inspection, repair, upgrade, modular assembly, and construction of space assets.

1. *Servicing* is the alteration of a spacecraft after its initial launch
2. *Assembly* involves aggregation and connection of components to create a spacecraft or module
3. *Manufacturing* involves transformation of raw materials into usable spacecraft components

OSAM can vastly expand the performance, availability, and lifetime of space systems compared to the traditional paradigm. Incorporating the OSAM capabilities could decrease upfront cost and introduce pay-as-you-go options for deploying space assets, and it can enable spacecraft larger than launch vehicle fairing dimensions. OSAM capabilities leverage and foster an ecosystem that changes the space operations paradigm, creating the foundation for sustainable exploration and serving as a multiplier for other capabilities like space logistics, space power, and reusability.

This document compiles and organizes the current state of OSAM missions, capabilities, and developments. Understanding where the set of capabilities currently stand will help mission designers incorporate OSAM technologies into their concepts, create the starting point for technology development plans and roadmaps, and provide technologists a survey of the field they are developing. The authors recognize that this capability is broad and that they are unlikely to have captured everything that has been or is being done in the area on the first attempt. As a result, a new version of the *OSAM State of Play* will be released periodically, and the community is encouraged to submit any suggestions, corrections, and comments via an online survey at this link (survey will remain active through at least 10/1/2022):

- https://forms.gle/LPc8uG33phzVpVSE9

2 HISTORY OF OSAM

While OSAM is an emerging set of capabilities, previous achievements in this area have enabled ambitious space missions. The International Space Station, the Hubble Space Telescope, and the Mission Extension Vehicle demonstrate the dramatic operational missions that can be achieved using OSAM capabilities. Many current flight demonstrations are advancing areas that will enable the next generation of civil, national security, and commercial space missions.

Figure 1 provides an overview of operational missions that use OSAM and flight demonstrations that have advanced OSAM capabilities. After Hubble was launched in 1990, five Space Shuttle missions flew to the orbiting observatory for Extra Vehicular Activity (EVA) astronaut repair and upgrade of the systemin-space telescope. Engineering Test Satellite No. 7 (ETS-VII) was flown by Japan to demonstrate robotic servicing and was the first satellite that was equipped with a robotic arm. The International Space Station was assembled and serviced over multiple flights across several decades using a variety of vehicles from the United States (Shuttle), international partners (e.g. Soyuz, Progress), and industry (e.g. Dragon, Cygnus). The suite of Robotic Refueling Missions to the ISS have demonstrated the storage and robotic transfer of fluids using specialized tools as well as the robotic manipulation of cooperative and legacy spacecraft interfaces. Orbital Express was a joint DARPA and NASA mission that demonstrated RPO, refueling, and module replacement. Aboard the ISS, NASA's In-Space Manufacturing program has been able to demonstrate many manufacturing capabilities inside the pressurized volume. OSAM-1, OSAM-2, and Robotic Servicing of Geosynchronous Satellites (RSGS) are upcoming OSAM flight demonstrations that will advance servicing, assembly, and manufacturing capabilities for the future.

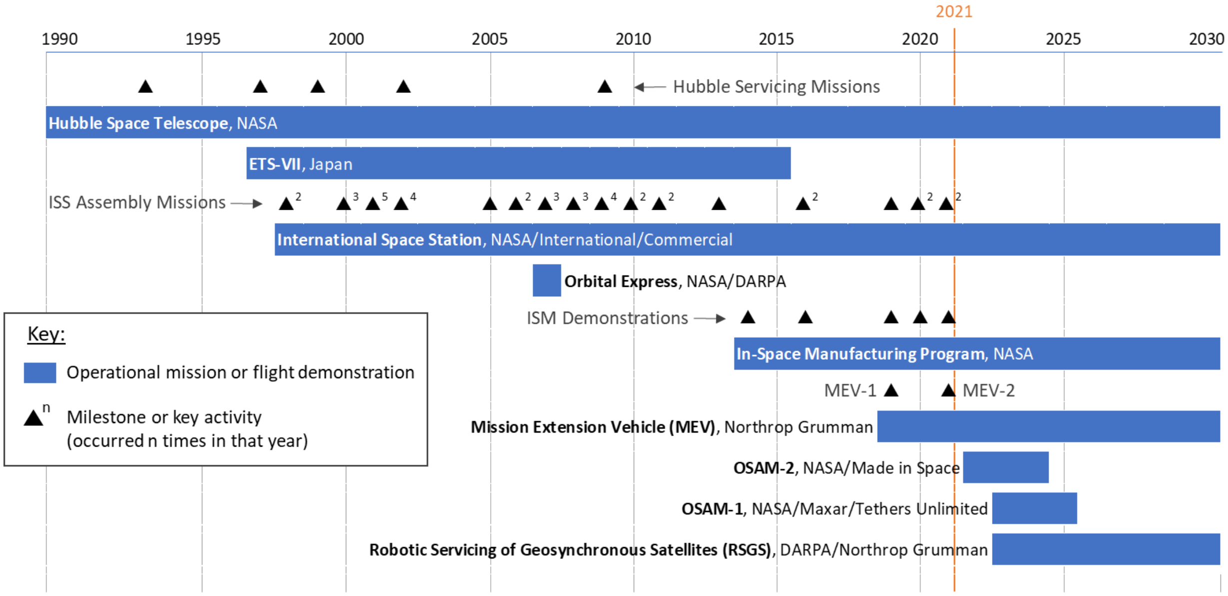


Figure 1: There is a long history of OSAM capabilities being used and advanced in ambitious operational missions (e.g., ISS, Hubble, and MEV) and flight demonstrations (e.g., Orbital Express). These missions and demonstrations have been performed by civil, national security, and commercial space organizations.

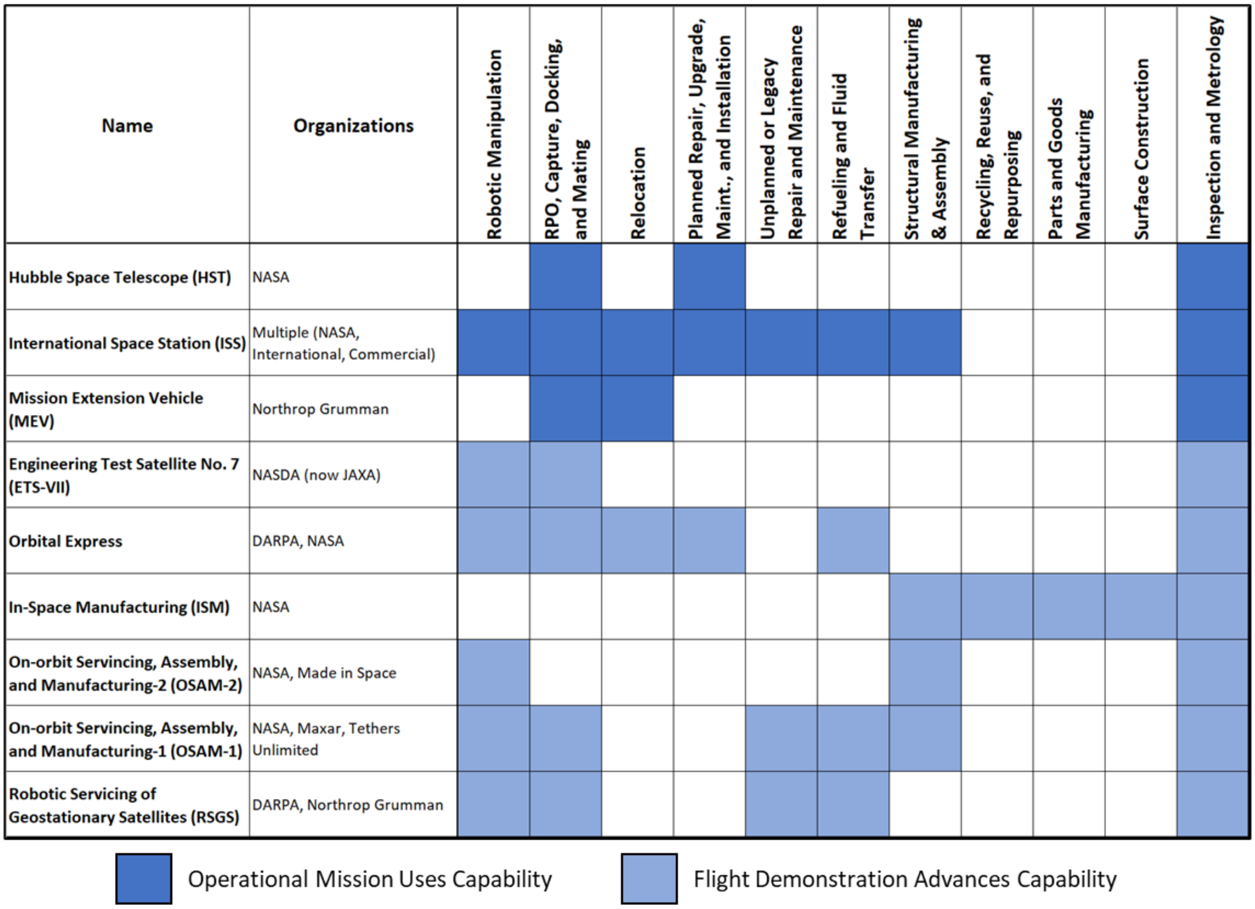
3 OSAM CAPABILITY AREAS

This document divides the OSAM capabilities into 11 capability areas that describe the functions or activities that would be performed in space using OSAM. These capability areas are distinct activities that an OSAM mission would perform, and several activities could combine to achieve a given mission. The 11 capability areas are:

- **Robotic Manipulation**: Involves manipulating payloads and spacecraft subsystems with a robotic manipulator. Includes robotic activities such as driving/releasing bolts, cutting, placing modules, and assisted deployment.
- **RPO, Capture, Docking, and Mating**: Involves two spacecraft maneuvering in proximity to each other and could include connecting the two spacecraft together. Includes crewed or autonomous docking/berthing, remote inspection, and formation flying.
- **Relocation**: Involves one spacecraft maneuvering another spacecraft into a new orbit or orientation. Includes boosting, repositioning, deorbit, debris removal, and life extension.
- **Planned Repair, Upgrade, Maintenance, and Installation**: Involves adding or replacing components on a spacecraft that is prepared to receive those components. This is done to repair or upgrade that component, perform a maintenance swap-out, or install a new component that expands the capability of the spacecraft. Includes systems with modular interface connections and payload/component swap-out or upgrade.
- **Unplanned or Legacy Repair and Maintenance**: Involves adding or replacing components on a spacecraft that was not intended to receive those components. Includes more complex operations to access the interfaces and make new connections.
- **Refueling and Fluid Transfer**: Involves transferring fluid from one spacecraft to another. Includes cryogenic and non-cryogenic propellants/fluids and transfer in orbit or on a planetary surface.
- **Structural Manufacturing and Assembly**: Involves creating or assembling structures in space to create spacecraft components or subsystems. Includes manufacturing (3-D printing, extruding, etc.) and assembly of structures with various interfaces, joining approaches, and precision.
- **Recycling, Reuse, & Repurposing**: Involves the use of spacecraft components already in space in a new spacecraft. Includes recycling the material from old spacecraft parts for new manufacturing feedstock and reusing old spacecraft parts as-is in new spacecraft.
- **Parts and Goods Manufacturing**: Involves creating spare parts, subsystems, and components for use in space or on a planetary surface. Includes internal (to a habitat) and external manufacturing with multiple materials and sizes.
- **Surface Construction**: Involves excavating, constructing, and outfitting structures and infrastructure on a planetary surface. Includes horizontal (landing pads, roads, etc.) and vertical (power, habitation, etc.) construction, using regolith to build, and assembly of erected structures.

- **Inspection and Metrology:** Involves observation of systems in space to understand their configuration, size and shape, or other features of interest. Includes free-flyer inspection, non-destructive evaluation, close (robotic) inspection, and space situational awareness.

Figure 2 indicates the capability areas that are used or advanced in the operational missions and flight demonstrations from Figure 1. The capability areas that have been incorporated the most are Inspection and Metrology; RPO, Capture, Docking, and Mating; and Robotic Manipulation. ISS, through its assembly and servicing missions, uses the most OSAM capabilities that have heavily involved astronauts. ISS has also been a platform that supports other demonstration missions (e.g., Robotic Refueling Missions and In-Space Manufacturing program) that advance capabilities in OSAM and other areas. Technologies in every capability area have been used or demonstrated on orbit.



Name	Organizations	Robotic Manipulation	RPO, Capture, Docking, and Mating	Relocation	Planned Repair, Upgrade, Maint., and Installation	Unplanned or Legacy Repair and Maintenance	Refueling and Fluid Transfer	Structural Manufacturing & Assembly	Recycling, Reuse, and Repurposing	Parts and Goods Manufacturing	Surface Construction	Inspection and Metrology
Hubble Space Telescope (HST)	NASA		■		■							■
International Space Station (ISS)	Multiple (NASA, International, Commercial)	■	■	■	■	■	■	■				■
Mission Extension Vehicle (MEV)	Northrop Grumman		■	■								■
Engineering Test Satellite No. 7 (ETS-VII)	NASDA (now JAXA)	▨	▨									▨
Orbital Express	DARPA, NASA	▨	▨	▨	▨		▨					▨
In-Space Manufacturing (ISM)	NASA							▨	▨	▨	▨	▨
On-orbit Servicing, Assembly, and Manufacturing-2 (OSAM-2)	NASA, Made in Space	▨						▨				▨
On-orbit Servicing, Assembly, and Manufacturing-1 (OSAM-1)	NASA, Maxar, Tethers Unlimited	▨	▨			▨	▨	▨				▨
Robotic Servicing of Geostationary Satellites (RSGS)	DARPA, Northrop Grumman	▨	▨			▨	▨					▨

■ Operational Mission Uses Capability ▨ Flight Demonstration Advances Capability

Figure 2: Operational missions and flight demonstrations have used and advanced OSAM capabilities. Robotic Manipulation; RPO, Capture, Docking, and Mating; and Inspection and Metrology capability areas have been used in most of these missions, and ISS has used and demonstrated many of these OSAM capability areas.

This document collects previous and ongoing OSAM development activities and technologies to describe the current state of OSAM. Each activity or technology collected is categorized into one or more of the capability areas as entries into a repository (these activities and technologies are referred to collectively as "entries" through the rest of this document). Figure 3 presents the total number of entries for each capability area. Again, Robotic Manipulation and RPO, Capture, Docking, and Mating are the most prolific. Many of the nascent or forward-looking capability areas such as Recycling, Reuse, and Repurposing have fewer activities.

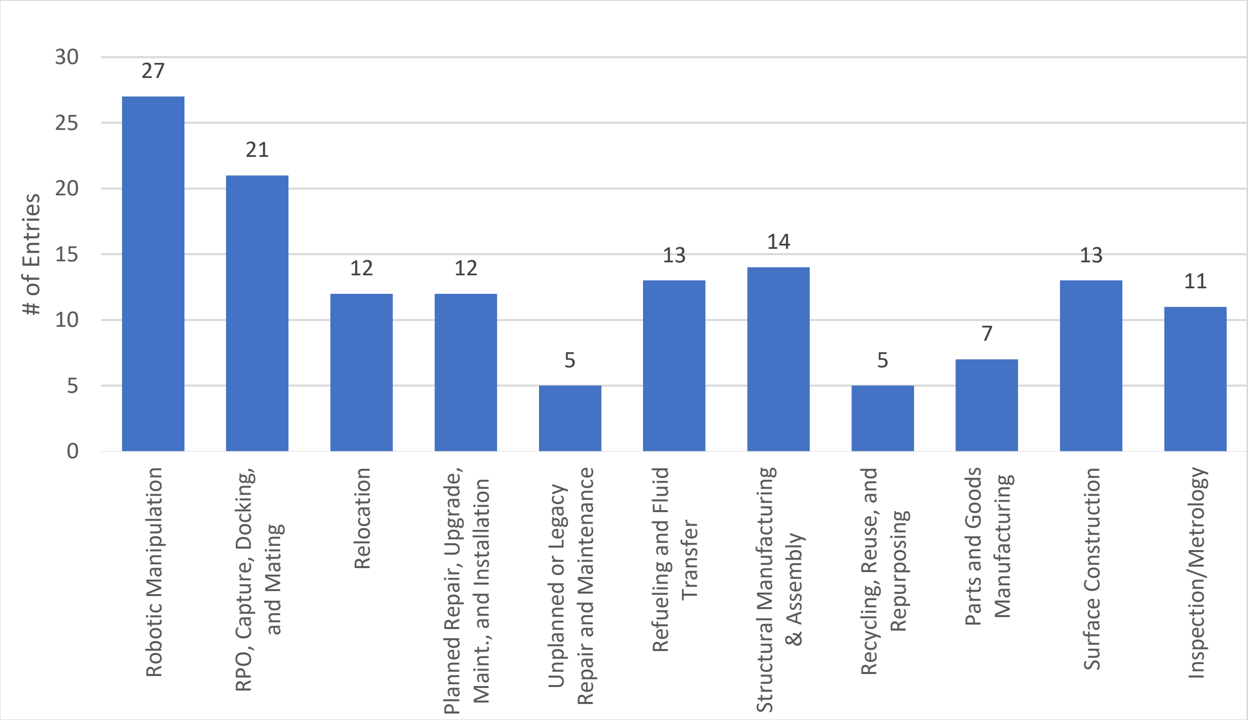


Figure 3: The activities or technologies collected in this document are categorized into the capability areas. This bar chart represents the number of activities in each capability area and is sorted by the total number of activities in each area.

Each capability area section below contains an overview, the current state, and the planned developments of that capability area. The current state includes systems or components that have been flown, demonstrated on the ground, or have hardware under development. Together, the information provides a current view of the capability area and where that capability area is headed in the future. More details on the entries for each capability area can be found in the appendix, which also contains information about the use/demonstration date, developing organization, country of origin, and select performance parameters.

3.1 ROBOTIC MANIPULATION

Robotic manipulation is the capability to manipulate payloads, subsystems, or other spacecraft. A robotic manipulator can grapple a spacecraft during rendezvous and capture, place new modules on an existing spacecraft or platform, perform intricate actions like cutting or welding, and could assist deployment of large structures like solar arrays.

There are different categories within the robotic manipulation capability area based on the scale of the robotic manipulator and where it is used. Long reach manipulators have lengths greater than 8 meters and have been used in microgravity to manipulate large space systems. Short reach manipulators with lengths less than 8 meters have been used on a spacecraft in microgravity and on surface systems like landers and rovers. A summary of the robotic arms that have flown and that are under development is presented in Figure 4.

Long reach manipulators have flown in space to support human exploration. The Shuttle Remote Manipulator System (SRMS) and Space Station Remote Manipulator System (SSRMS), also known as Canadarm and Canadarm2 respectively, have supported NASA's human space exploration missions since 1981. These robotic manipulators are teleoperated and support latching and end effectors that attach to common grapple fixtures.

Short reach manipulators such as the Special Purpose Dexterous Manipulator (Dextre) and the JAXA Small Fine Arm (SFA) have been used to support servicing activities and experiments aboard the International Space Station. Both Dextre and SFA attach to the end of long reach manipulators that place them near their tasks. Short reach manipulators have also been prevalent on the Martian surface onboard landers and rovers such as Phoenix, Curiosity, and Perseverance to assist with experiments, digging, sample collection and handling, and other complex tasks.

New developments are being worked in these various categories within the robotic manipulation capability area. Planned long reach manipulators, such as the Tendon-Actuated Lightweight In-Space MANipulator (TALISMAN), would provide mass and packaging efficiencies for microgravity operations. On the surface, extreme environments (dust, temperature, lighting conditions) are driving requirements of manipulators like the Lightweight Surface Manipulator System (LSMS) for payload offloading and handling and surface operations. Several short reach manipulators are in development to support servicing, assembly, and manufacturing (NASA Servicing Arm and FREND). Commercially, the trend in robotic manipulation is away from expensive, bespoke, human-operated manipulators and toward proliferated robotics in space with low cost, autonomous operations that will support OSAM needs in the future.

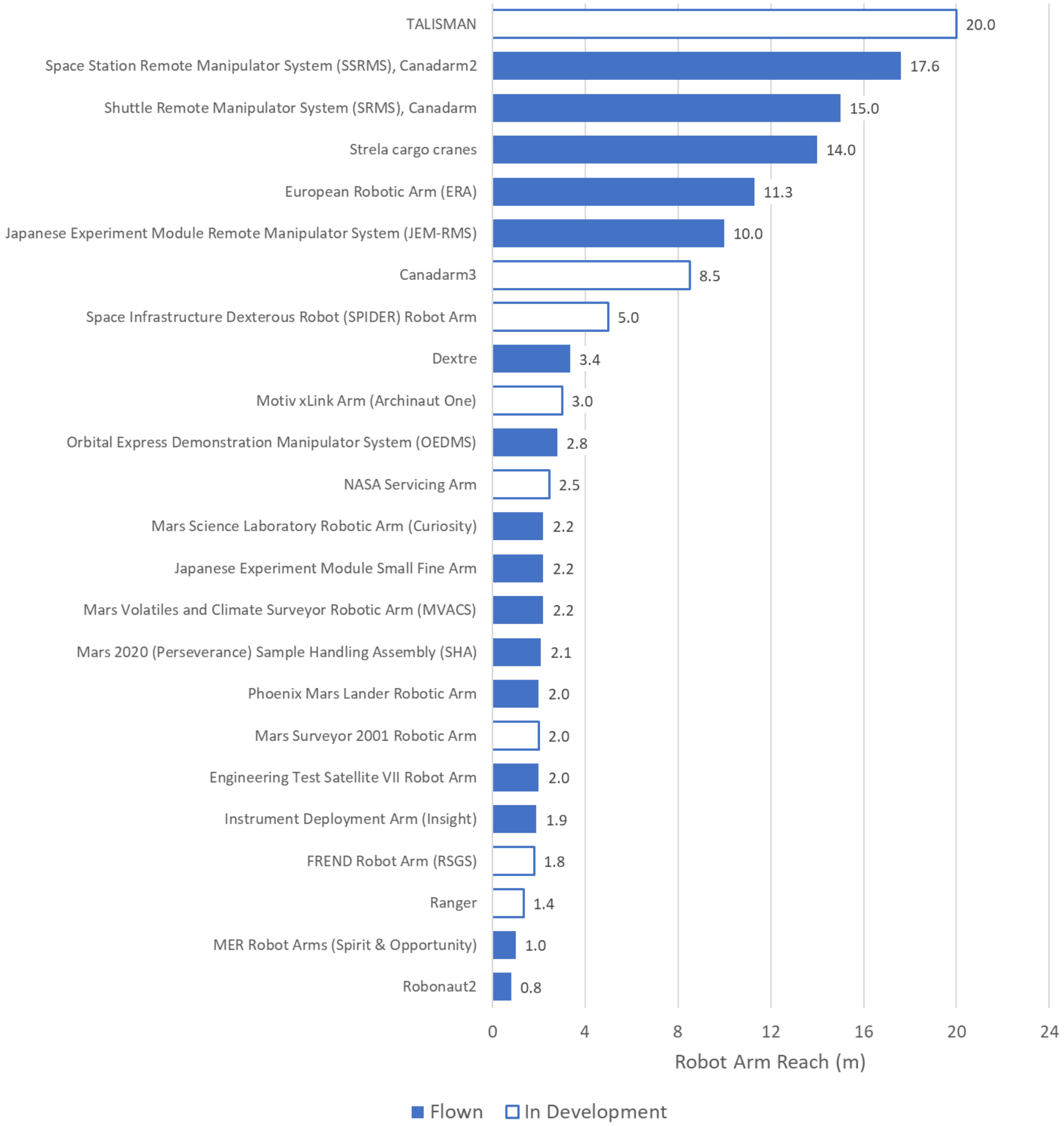


Figure 4: Robotic manipulators have flown for a variety of missions, from surface robotics to long reach manipulation on ISS. Many are being developed to increase autonomy, reduce cost, and proliferate the use of space robotics.

3.2 RPO, CAPTURE, DOCKING, AND MATING

RPO, Capture, Docking, and Mating is the capability area which enables interaction between spacecraft. RPO is the action of a satellite making maneuvers with consideration of another satellite's orientation or orbital parameters. Capture is the ability of a typically larger satellite to grasp a typically smaller, passive satellite for the purposes of spacecraft mating. Docking refers to the ability of a satellite to maneuver itself properly to mate with another spacecraft. Mating refers to the operations which will allow two spacecraft to physically join in space. RPO, capture, docking, and mating is required for any satellite interaction and is therefore needed for operation of technologies which contribute to other capability areas, such as relocation, planned and unplanned servicing, refueling and fluid transfer, and structural manufacturing and assembly. For this reason, RPO, capture, docking, and mating is one of the most cross-listed capability areas, as shown in Figure 3.

The first docking in space occurred during the Gemini VIII mission on March 16, 1966. Shortly after, the first autonomous docking was demonstrated with the mating of the unmanned Kosmos 186 and the unmanned Kosmos 188 on October 30, 1967. Since these initial operations, innumerable examples of RPO, capture, docking, and mating have occurred in space. The construction and maintenance of the ISS has contributed to significant advancement in this capability area due to the number of missions which include RPO and autonomous docking by vehicles such as Soyuz, Progress, Dragon Cargo, and Dragon Crew.

Major advancement towards fully autonomous mating of unmanned spacecraft has been in progress since the Japanese ETS-VII mission in 1998, which demonstrated utility for unmanned rendezvous and docking techniques. Two AFRL micro-satellite missions in 2003 and 2005 demonstrated RPO with an active and inactive target. In 2007, Orbital Express demonstrated automated rendezvous and capture, transfer of propellant, and transfer of a spacecraft component.

Servicing satellites which maneuver, transfer fuel, or complete repairs on an incapacitated satellite must first perform RPO, capture, docking, and mating operations. To that end, the state-of-the-art for RPO, capture, docking, and mating has recently advanced through development of servicing satellites, such as Northrop Grumman's MEV-1 and MEV-2. Future missions, such as Tethers Unlimited's LEO Knight, Northrop Grumman's MRV, and NASA's OSAM-1, will advance the state-of-the-art of RPO, capture, docking, and mating for use during in-space assembly missions. Figure 5 shows a breakdown of entries for the target spacecraft size in currently planned RPO, capture, docking, and mating missions. In the figure, the distribution of contact versus non-contact missions is highlighted. Contact includes any physical interaction with the target satellite while non-contact refers to only observational interaction, such as RPO.

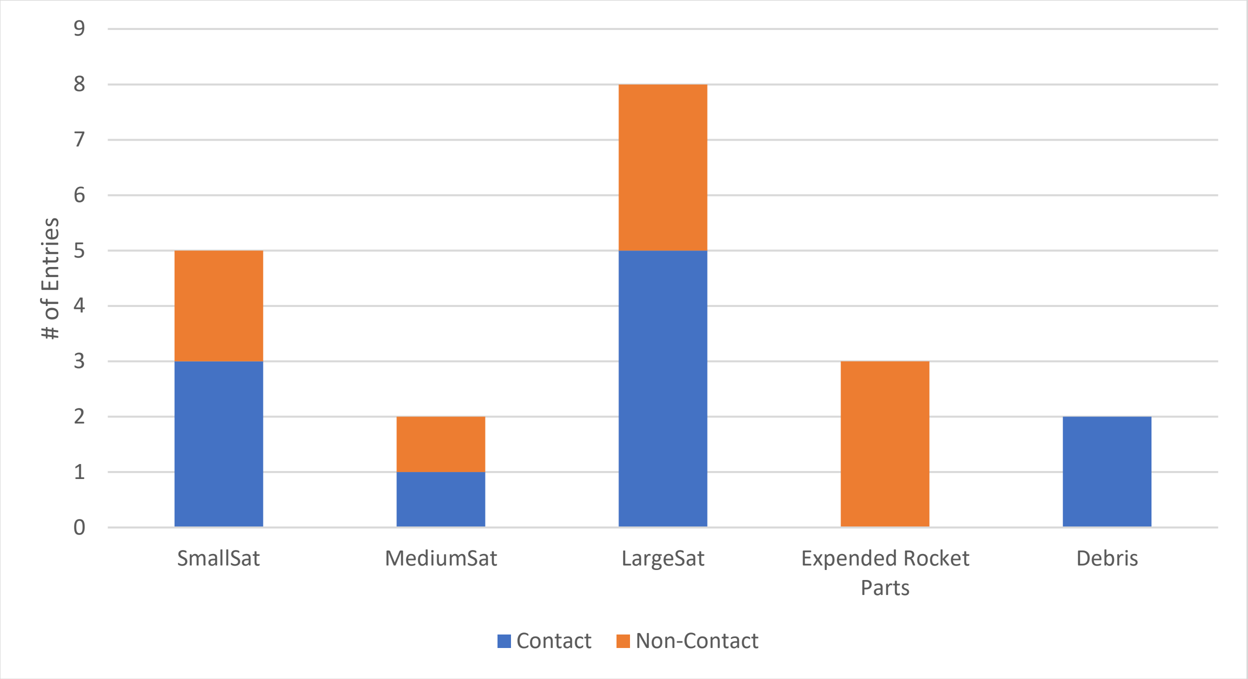


Figure 5: RPO, capture, docking, and mating technologies are useful for a wide range of client types. While most interest is focused on interaction with active satellites, this capability area is also used for managing expanded components or space debris.

3.3 RELOCATION

Relocation refers to the capability of one spacecraft to alter the orbital parameters or orientation of another satellite. The purpose of relocation can be to remove retired satellites from an active orbit, to move space debris to a more desirable location, or to extend the lifetime of a satellite with depleted fuel. The operation of the ISS has required relocation services on multiple occasions since it's installation, including boosting by visiting cargo vehicles to maintain orbit and reorientation of vehicles prior to berthing. The Space Shuttle was also responsible for many in space relocation activities, such as delivery of satellites to orbit or reorientation of satellites prior to deployment from the Space Shuttle cargo bay.

Relocation of space debris was first demonstrated on orbit in 2016 with China's Aolong-1 mission. Similar to Aolong-1, Astroscale's ELSA-d mission is focused on the relocation of end-of-life satellites from an active orbit to a graveyard orbit. The ELSA-d mission was launched and completed its first technology demonstration for capture of satellite space debris in 2021.

In addition to development in space debris removal, relocation technology has also developed through mission extension style missions. Northrop Grumman's MEV-1, MEV-2, and Mission Extension Pods provide mission extension services to commercial payloads. These mission extension type satellites are ideal for customers who may not have the time or resources to launch a replacement for an end of life satellite. While MEV-1 and MEV-2 are both currently operating on orbit, Mission Extension Pods is currently in development, and will interact with the Mission Robotic Vehicle that launches in 2024. The Northrop Grumman satellite lifetime extension spacecraft are all designed to operate strictly in GEO.

Future development in this capability area is currently heavily focused on space tugs, satellites which will offer orbital relocation for satellites which may not typically have the capability of large orbital changes, and rideshare upper stages, which are capable of delivering clients to multiple orbits. ESPA-based space tug satellites are currently in development by MOOG and Firefly Aerospace while Momentus is developing Vigoride as a rideshare option.

As many of these relocation technologies are designed to operate in specific orbits, Figure 6 shows the operational orbits of each technology. As shown in the figure, current activities are heavily focused on relocation capabilities within LEO and GEO. Future missions, including the Firefly Aerospace Space Utility Vehicle, are expanding relocation capabilities towards operations beyond GEO into xGEO, or cislunar orbits.

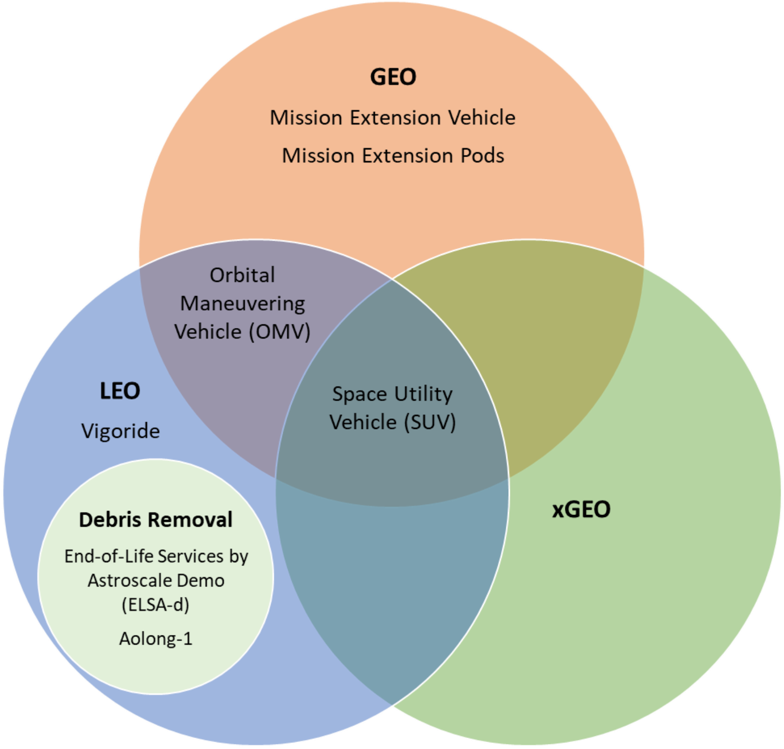


Figure 6: Relocation capabilities are currently heavily focused on LEO and GEO orbital regimes, and on commercial spacecraft targets. Of the technologies included in the figure, Aolong-1, ELSA-d, and MEV have been demonstrated on orbit. Progress has been made towards relocation of orbital debris in LEO through the ELSA-d and Aolong-1 missions and future capabilities into xGEO space is currently in development through the Firefly Aerospace Space Utility Vehicle.

3.4 PLANNED REPAIR, UPGRADE, MAINTENANCE, AND INSTALLATION

Planned repair, upgrade, maintenance, and installation is the capability to service or augment an existing spacecraft that is designed to receive that service. Unlike legacy systems that are not expected to be visited again once on orbit, a prepared spacecraft is designed with the servicer or assembly agent in mind before launch. This is the center of an OSAM ecosystem where the client vehicle and OSAM servicing agents are co-designed to operate together and enable new missions and capabilities in the future.

Key to this OSAM ecosystem are standardized, interoperable interfaces for mechanical, fluid, power, data, and to a lesser extent, thermal connections between two spacecraft. Several providers have developed modular interfaces and aids to perform OSAM functions to a spacecraft. The trend in this area is toward all-in-one modular interfaces that provide multiple connections in one interface (e.g., mechanical, power, and data).

Some of these interfaces have flown in space before. The interfaces between elements of the International Space Station enabled the modular assembly and servicing of the platform, and Hubble, which was designed to be serviced, was serviced five times by astronauts aboard the Space Shuttle. External payload platforms on ISS (e.g., JEM-EF, Bartolomeo) enable experiments and payloads to attach to the ISS to take advantage of the unique space environment. Other interfaces and modular spacecraft that have flown in space, such as Altius's mechanical interface, Dog Tag (which flies on OneWeb satellites) and Novawurks's HISat modular spacecraft bus with a 4-in-1 interface. There are several prototypes and ground test units for mechanical, fluid, power, data, and thermal interfaces being developed as well. NASA's Robotic Refueling Mission (RRM) used custom robotic tooling to demonstrate the capability to interface (engage, manipulate, and release) with modular spacecraft components.

These interfaces are designed for different orders of magnitude spacecraft from CubeSats to large spacecraft. Figure 7 illustrates the scale for mechanical load, power, and data rate for some of the interfaces that have been flown or are under development.

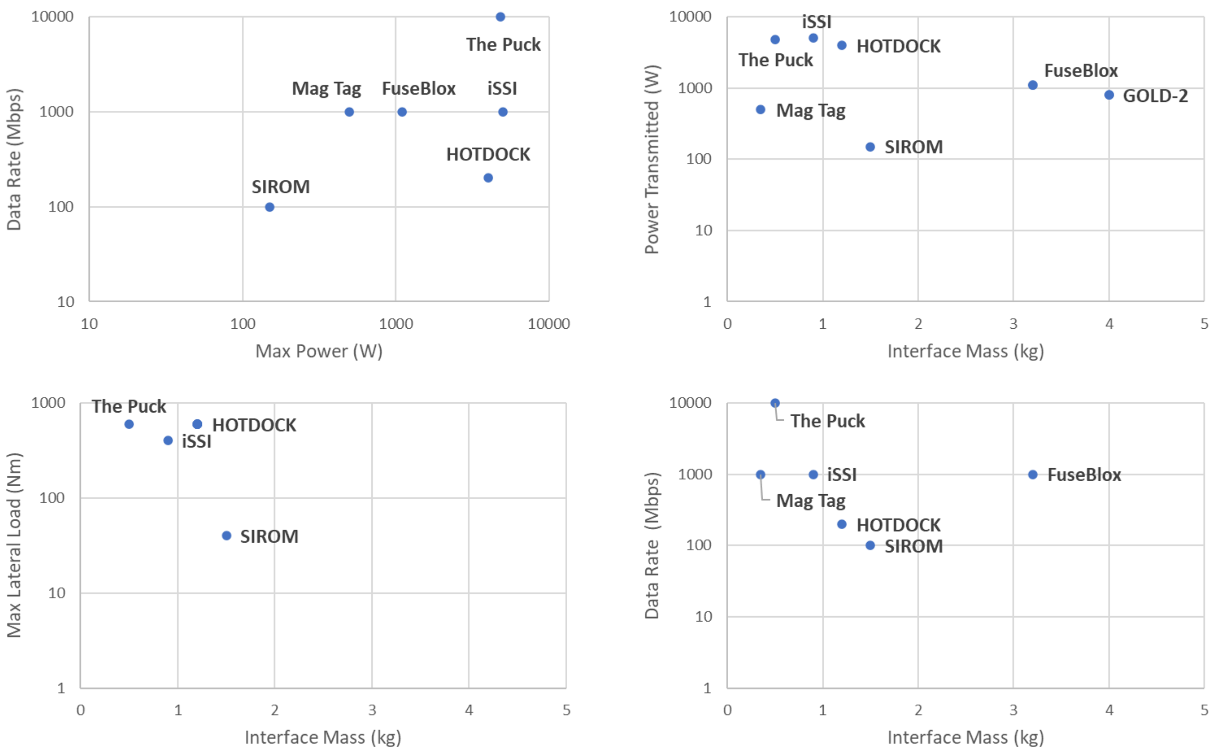


Figure 7: Modular interfaces are being developed to support multiple types of spacecraft to create an OSAM ecosystem where clients and OSAM agents can readily create mechanical, fluid, power, data, and thermal connections. This figure presents some of the interfaces in use and under development.

3.5 UNPLANNED OR LEGACY REPAIR AND MAINTENANCE

Unplanned or legacy repair and maintenance is the capability to service existing spacecraft that were not designed to take advantage of the OSAM capabilities. These services include refueling, module repair and/or replacement, and augmentation of the spacecraft. This capability is distinct from “planned” servicing because the services being provided may need mission-specific functionality that could require unique capabilities to access, remove, and install parts or modules. These capabilities are also important for missions like debris removal, scavenging, and manipulating “dead” or damaged satellites whose cooperative functionality is compromised.

While much of the focus on creating an OSAM ecosystem relies on the servicing vehicle and the client vehicle to be co-designed to take advantage of OSAM capabilities, there are activities that are focused on servicing legacy vehicles. While Landsat 7 was not intended to be serviced during its operational lifetime, NASA’s OSAM-1 mission (formerly Restore-L) will provide refueling and relocation services to the spacecraft in orbit. Extra functionality is required on the client servicer to access the fluid fill valves, complexity that would not be required if the client were designed to accept propellant on orbit.

NASA’s OSAM-1 and DARPA’s RSGS missions are key government flight demonstrations currently planned that will advance the unplanned or legacy repair and maintenance capability area. Commercial servicers are also looking to address some needs of legacy spacecraft while reducing the complexity needed to interface with an unprepared client vehicle. For example, mission extension pods would augment a spacecraft without needing to access any internal components, the LEO Knight system is targeting small satellites in LEO, and existing known interfaces (e.g., the Marman ring on Landsat 7 that OSAM-1 is grappling) can simplify the servicer operations.

3.6 REFUELING AND FLUID TRANSFER

Refueling and fluid transfer is the capability to move fluid from one spacecraft to another. This can be done to extend the life of a system, augment its capability beyond what a single launch can deliver, and/or enable reusable transportation systems. The most mature fluid transfer capability is that of storable fluids, which covers fluids that do not require active cooling to remain liquid, such as water, hydrazine, and nitrogen tetroxide (NTO). Cryogenic fluids, such as liquid oxygen, hydrogen, or methane, provide performance benefits as a propellant and are often used in large human-scale exploration systems. A summary of the various activities that have been performed in refueling and fluid transfer are presented in Figure 8.

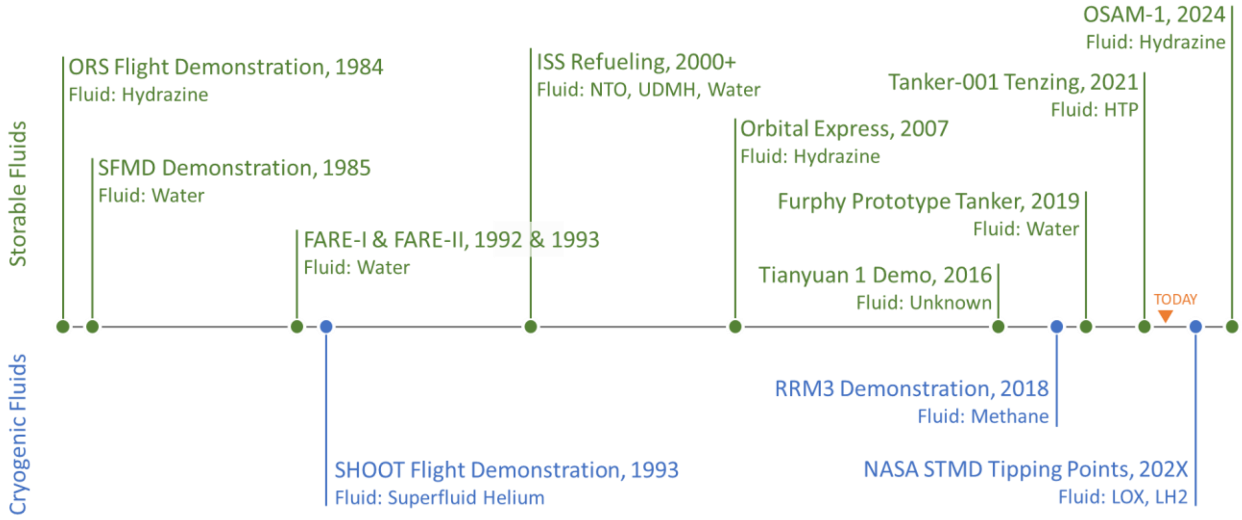


Figure 8: Storable fluid transfer has been demonstrated many times, including in operational missions like the ISS. The future is heading toward commercial refueling services (especially for storable fluids) and demonstrations are planned to test large-scale cryogenic fluid transfer in space.

Several storable fluid storage and transfer demonstrations occurred on various Space Shuttle missions (e.g. ORS, SFMD, FARE) in the 80s and 90s. Among other OSAM achievements, the Orbital Express flight demonstration transferred hydrazine between two spacecraft. The most prolific refueling capability comes from the Russian Progress vehicle which first refueled Salyut 6 in 1978 and has been used to refuel ISS with hydrazine, NTO, and water since 2000.

Historically, very little has been demonstrated for in-space cryogenic fluid management and transfer. However, future missions will rely on cryogenic propellants, so multiple flight demonstrations are in development. The Superfluid Helium On-Orbit Transfer (SHOOT) flight demonstration on STS-57 transferred a cryogenic fluid (superfluid helium) between tanks using some special properties of that fluid. Therefore, the techniques used are not necessarily applicable to other cryogenic fluids such as liquid oxygen or liquid methane. The Robotic Refueling Mission 3 (RRM3) in 2019 was able to prove cryogenic fluid storage, successfully demonstrating robotic manipulation of the cryogenic tools, fittings, and hoses to enable the transfer, but a system failure inhibited the fluid transfer demonstration. In 2020, NASA awarded four Tipping Point awards to demonstrate cryogenic fluid management, storage, and transfer of liquid oxygen and liquid hydrogen in space.

The future of this capability area appears to be heading toward commercial propellant resupply services – both storable and cryogenic. Orbit Fab launched the first propellant depot with its Tanker-001 Tenzing, storing High-Test Peroxide (HTP) propellant. The NASA Tipping Point demonstrations are advancing technologies for cryogenic propellant storage and transfer to support large missions of the future (e.g., human lunar missions).

3.7 STRUCTURAL MANUFACTURING AND ASSEMBLY

Structural Manufacturing and Assembly is the capability to produce structures in space out of components delivered from Earth. A major use case of this capability area is production of structures which exceed the typical payload volume constraint of launch vehicles. Technologies which contribute to this capability area are wide ranging due to the complexity of positioning and joining structural elements in space. A summary of the technologies pertinent to this capability area and the type of technology is shown in Figure 9. In contrast with deployable space structures, which can also produce on-orbit structures larger than launch volume constraints, structural manufacturing and assembly enables the ability to launch standard structural components, reduces the need for intricate deployable design, and allows for on-orbit structural reconfigurability.

Although current developments within the realm of structural manufacturing and assembly involve the use of robotics, NASA initially explored the possibility of human achieved structural manufacturing and assembly through the EASE/ACCESS space shuttle flight experiments in 1985, which studied the astronaut efficiency, fatigue, and construction techniques for assembling space structures. The construction of the ISS included extensive use of structural manufacturing, completed through use of robotics and human construction. Construction of the ISS began in November of 1998 and the first resident crew arrived in November of 2000.

In-space demonstrations of structural manufacturing and assembly are slated for demonstration through the OSAM-1 and OSAM-2 missions. During the OSAM-1 mission, Maxar's SPIDER robotic arm will assemble seven structural elements to form a functional 3-meter communications antenna and the payload will manufacture a proof-of-concept 10-meter composite beam. The OSAM-2 mission will demonstrate the ability to 3D print two 10-meter beams, which will support solar panels to produce 5 times the power of similarly sized satellites.

Progress in the structural manufacturing and assembly capability area has also been made through recent ground demonstrations, including demonstrations of NINJAR and SAMURI at NASA Langley in 2017 and

Assemblers at NASA Langley in 2021. These demonstrations are focused on the robotic and autonomous positioning and joining of standard structural elements.

	Robotic Arm	Robotic Arm Joint	Deployable Structures	Structural Joint	Human Assembly	Robotic Assembly
Space Infrastructure Dexterous Robot (SPIDER)	🟩					
OSAM-2 Motiv Robotic Arm	🟩					
Assemblers	🟨					
Hinge for Use in a Tension Stiffened and Tendon Actuated Manipulator		🟨				
SHEAth-based Rollable Lenticular-Shaped and Low-Stiction (SHEARLESS) Composite Booms			🟨			
Structural Joint With Multi-Axis Load Carrying Capability				🟦		
Robotically Compatible Erectable Joint with Square Cross-Section		🟩				
NASA Intelligent Jigging and Assembly Robot (NINJAR)						🟨
Strut Attachment, Manipulation, and Utility Robotic Aide (SAMURAI)						🟨
Joint Design Using Electron Beam Welding for Autonomous In-Space Truss Assembly (EBW Joint)				🟨		
Beam Fabricator						🟩
Archinaut						🟩
EASE/Access					🟦	
Precision Assembled Space Structures (PASS)						🟨

🟦 Completed Flight Demonstration

🟩 Scheduled On-Orbit Demonstration

🟨 In Development

Figure 9: The technologies which contribute to the capability of structural manufacturing and assembly are wide ranging, due to the complexity of the process. The current advancement in this capability area focuses on robotic structural manufacturing and assembly.

3.8 RECYCLING, REUSE, AND REPURPOSING

Recycling, reuse, and repurposing is the capability to use spacecraft parts and materials already in space for a new purpose. This includes breaking down materials like polymers and metals for use in in-space manufacturing, reforming existing components into shapes that perform a different function and repurposing full spacecraft components (e.g., tanks, structural members, electronics) in new ways. Recycling, reusing, and repurposing materials in space reduces the logistics chain needed, takes advantage of the mass and volume of items launched that do not serve another purpose beyond their primary function otherwise, especially for long duration missions without regular opportunities to visit, such as human Mars missions. Essentially, recycling, reuse and repurposing include spacecraft components and materials as part of the "native" resources available for sustained presence.

The ReFabricator was installed on ISS in 2019 and was intended to have the capability to recycle printer polymer parts into filament feedstock for further manufacturing. However, upon startup, an anomaly in the recycling system occurred. This capability would enable purpose-built parts to be created and then recycled for use later in the mission, fabricating items only as needed, thus reducing the logistics needed at the beginning of the mission.

The future in this nascent capability area is in expanding the materials that can be reused in space, tailoring the performance of those materials for use in the space environment, and understanding the mission implications of this capability. Ground demonstrations for recycling of metal (e.g., MAMBA) and multiple different polymers are beginning to expand the capability of recycled materials. Studies on the use of recycled materials for long duration missions and reusing parts such as tanks and structural members from landers are broadening the potential use cases of this capability for future missions.

3.9 PARTS AND GOODS MANUFACTURING

Parts and goods manufacturing is the capability of producing components in-space from stock materials which have been traditionally delivered from Earth. Parts, which refers to spacecraft components, and goods, which refers to items readily available on Earth, are often delivered from Earth to the ISS for spacecraft repair or astronaut use. The primary benefit of parts and goods manufacturing in-space is the ability to quickly produce a component when needed, as opposed to waiting for delivery of that component from Earth. This capability may prove crucial in time sensitive situations or in situations where delivery of a component from Earth is unrealistic, such as a human mission to Mars. Technologies which have been demonstrated in-space thus far rely on delivery of stock material from Earth, but technologies are in development which would allow for future in-situ resource utilization.

The first demonstration of parts and goods manufacturing in space was in 2014 using a fused deposition modeling (FDM) 3D printer developed by Made in Space and operated in a Microgravity Science Glovebox (MSG). Made in Space next developed the Additive Manufacturing Facility (AMF), which was sent to the ISS in 2016 and remains a current installation. Both of the 3D printers developed by Made in Space and operated on the ISS printed plastic materials.

Current parts and goods manufacturing systems in development for use on the ISS, including the Techshot, Inc. SIMPLE and the Made in Space Vulcan, aim to add the ability to produce components from metal. In addition to additive manufacturing capabilities, the Vulcan will include subtractive CNC machining capabilities for final part processing. The introduction of on-demand metallic parts on the ISS will expand this technology use case to components which can endure high temperatures, stresses, and exhibit stiffness beyond the capability of plastics.

Development is also currently underway to explore the use of regolith to produce parts and goods on the ISS. RegISS, a 3D printer based on the AMF design and in development by Made in Space and Redwire, will use a regolith simulant feedstock blend to provide a proof of concept for future ISRU based feedstock 3D printing. The use of regolith in 3D printing is applicable to future human missions to the Moon or Mars where delivery of stock material from Earth is unrealistic. Figure 10 provides an overview of demonstrated and in development technologies in this capability area.

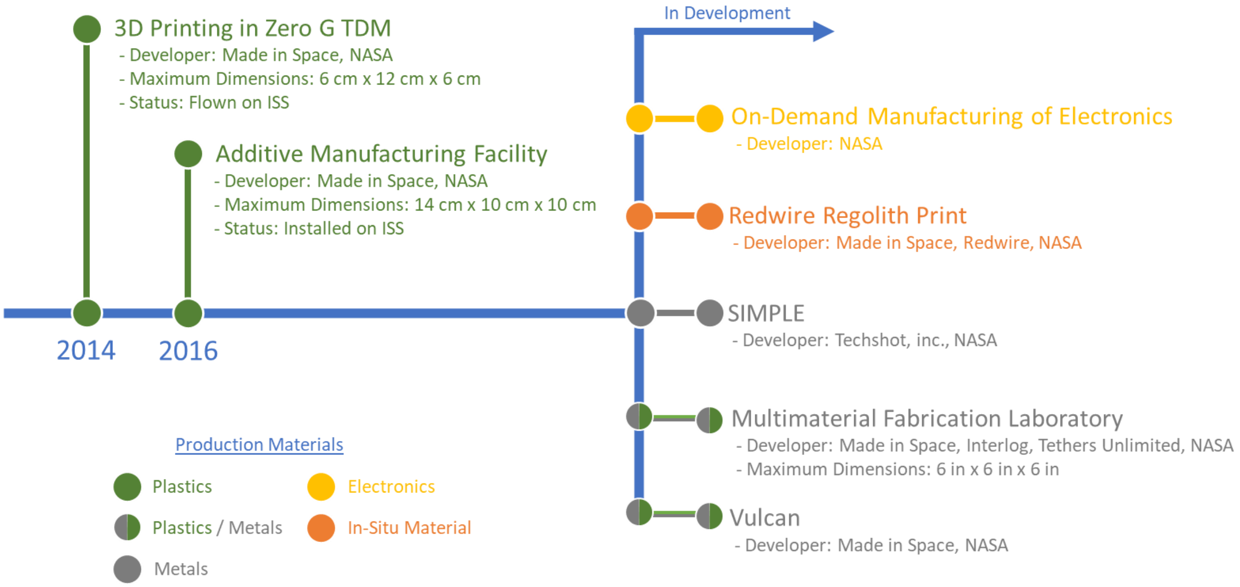


Figure 10: The first demonstrations of parts and good manufacturing in space began in 2014 with the use of 3D printed plastics. Current production techniques in development aim to expand the production capabilities to metals, electronics, and even ISRU-regolith infused feedstock. All technologies thus far have been tested or will be tested on the ISS.

3.10 SURFACE CONSTRUCTION

Surface construction involves excavating, constructing, assembling, and outfitting structures and infrastructure on a planetary surface. The scope of the structures to be built spans all phases and stages of a planetary surface structure, including horizontal (landing pads, roads, etc.) and vertical (power, habitation, etc.) construction. While initially the construction material must inevitably be Earth-sourced, Lunar regolith is expected to be a key source of future building material.

Lunar regolith is composed of several oxidized metals including iron, silicon, and aluminum oxides. By heating the regolith until it is reduced to a molten state, then passing electricity through the molten material, oxygen can be chemically separated from the oxide into gaseous form and the base metals recovered. The extracted regolith can also be blended with polymers into a feedstock for 3D printing. Excavation of any suitable construction site is expected to produce a significant amount of regolith material, and the availability of such in-situ resources is crucial to the maintenance of a habitat due to the time and expense of transporting any such materials from Earth.

The construction is further subdivided into via remote and autonomous means. The initial stages of excavation and construction are primarily via teleoperated platforms such as bulldozers, diggers, and cranes designed for operation in a low-gravity environment. Once the preliminary work is far enough along, autonomous systems are planned for incorporation to handle tasks such as processing the extracted regolith material and assembly of simple block structures, though the plans for such systems are still in very early stages. Figure 11 shows a condensed sequence of the technology from excavation to processing to construction.

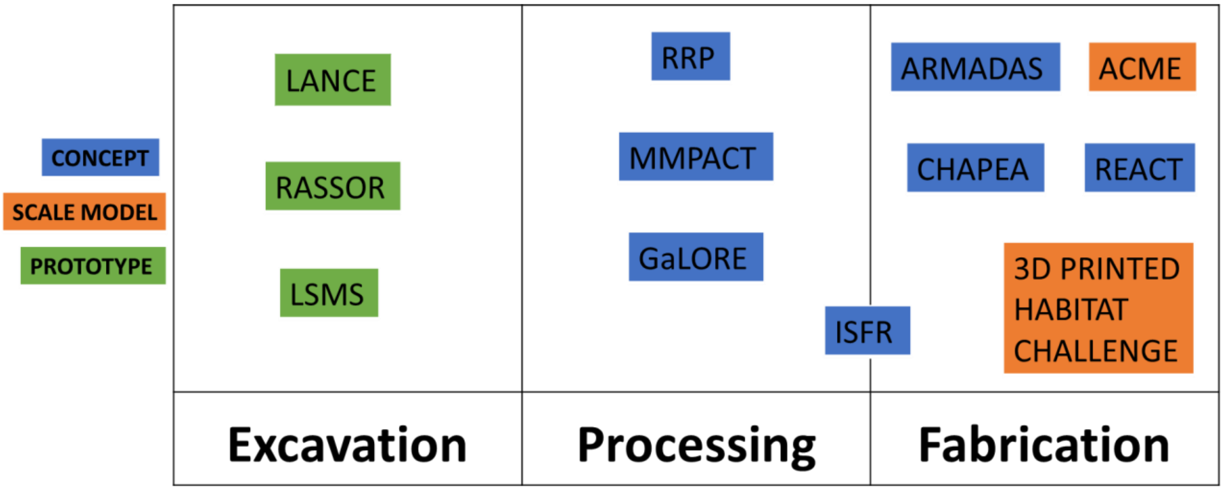
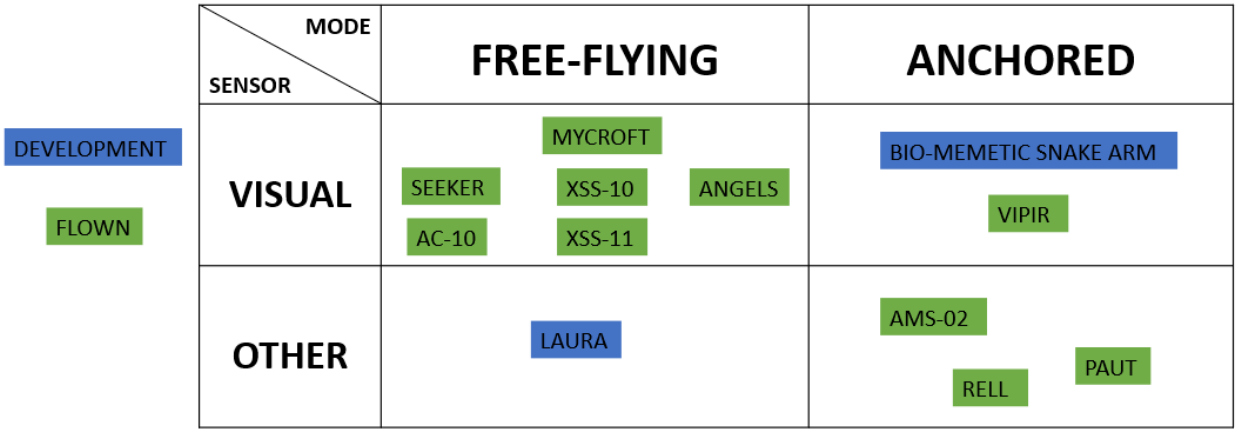


Figure 11: Surface Construction technologies, sorted into three main categories. Regolith excavation is the easiest category to simulate on Earth, reflected by it having the most advanced readiness level.

3.11 INSPECTION AND METROLOGY

Inspection and metrology involve the observation of systems, especially in space, to survey and analyze their location, configuration, size and shape, state of repair, and other features of interest; these observations can also include inspection of assembly and manufacturing processes, such as shapes of antennas. Spacecraft can suffer unexpected damage during their lifetimes from instrument failure or impacts with other vehicles, micrometeoroids, and other space debris. Observation can help to assess the threat of such collisions and possibly avoid them; in the event of damage or defect, inspection can evaluate the state of an asset and whether the mission is a loss or if the problem can be repaired or worked around. The scope of the analysis covers space situational awareness, free-flyer inspection, non-destructive evaluation, and close (robotic) inspection. Such inspection vehicles are often designed to navigate autonomously while sending the collected data for off-board analysis at a ground station.

Inspection is often carried out via high-definition cameras processing standard visual images, although other sensors such as ultrasound or multispectral are also possible depending on the particular inspection mission. The sensors are planned to be deployed from a variety of platforms, both anchored via a robot arm or free flying on a dedicated satellite vehicle. For example, NASA's VIPIR robotic multi-capability inspection tools were used on the ISS based RRM payloads to provide detailed close-up component inspections using a deployable, snake-like flexible hose with articulation capability. Real-time imagery was downloaded to ground based robotic operators. The ISS Robotic External Leak Locator (RELL) is a robotic tool used along with the SSRMS to scan (inspect) various areas of the ISS for signs of pressure increases indicative of ammonia leakage. This versatile tool has an integral mass spectrometer used to differentiate molecules within a pressure source and an ion gauge used as a general pressure gauge. The RELL tool can be used to support additional on-orbit planned and unplanned servicing needs as well as validating integrity of existing fluid systems and during fluid (refueling) transfers. The Bio-memetic snake arm robot was designed to be anchored to a surface of the ISS and conduct inspection and repairs in areas that would be difficult for a human to access. The Aerospace Corporation's AeroCube-10B satellite, one of a pair of 1.5U CubeSats deployed in concert, was designed to orbit around its dedicated partner AC-10A and record images with an on-board camera during operation. The XSS family of satellites, produced by the Air Force Research Laboratory, were designed without a permanent target, instead performing proximity inspections on dead or inactive space objects near each satellite's orbit. Figure 12 classifies the inspection platforms according to their mission types.



🟦 DEVELOPMENT

🟩 FLOWN

MODE / SENSOR	FREE-FLYING	ANCHORED
VISUAL	🟩 MYCROFT 🟩 SEEKER 🟩 XSS-10 🟩 ANGELS 🟩 AC-10 🟩 XSS-11	🟦 BIO-MEMETIC SNAKE ARM 🟩 VIPIR
OTHER	🟦 LAURA	🟩 AMS-02 🟩 RELL 🟩 PAUT

Figure 12: Inspection and Metrology technologies, sorted into four main categories. Free-flying visual platforms command by far the highest in-demand application of this technology area.

4 OSAM FACILITIES

Facilities provide an important resource in advancing OSAM capabilities. Figure 13 presents a summary of several facilities that have been used to advance these capabilities. While not exhaustive, the facilities shown within the Department of Defense, supporting Federally Funded Research and Development Centers (FFRDCs), NASA (centers and the ISS), and academia have been vital to advancing the capability areas discussed in this document and will continue to be a centerpiece to future OSAM development.

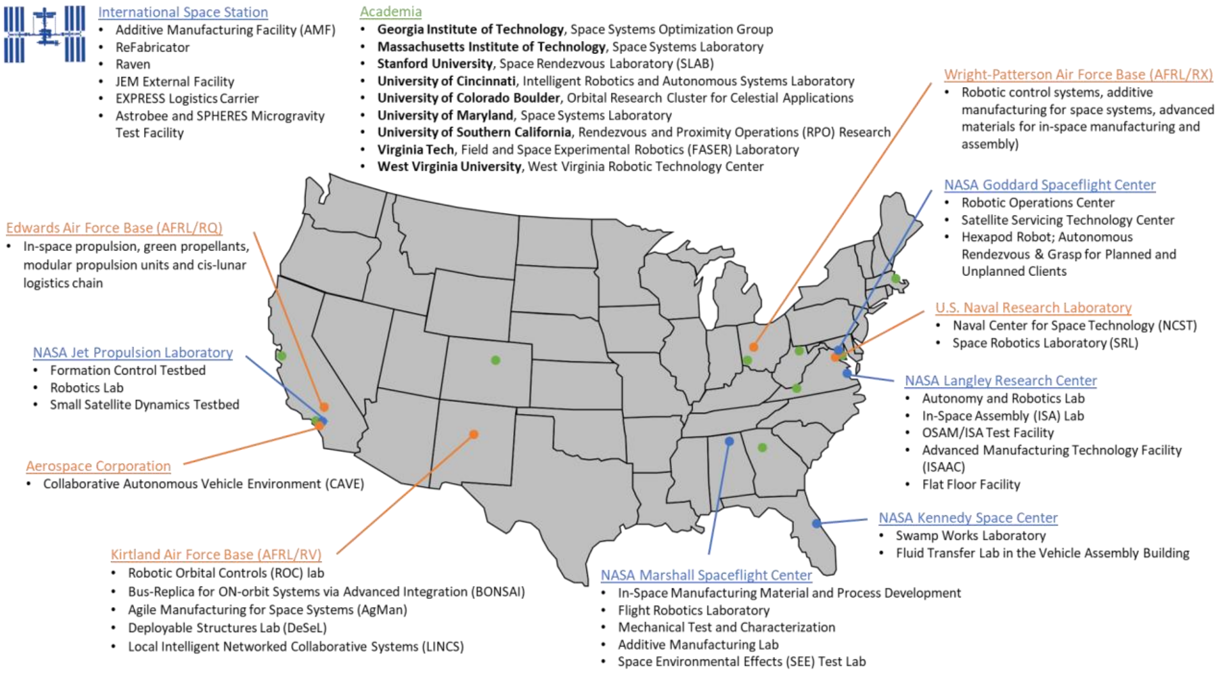


Figure 13: Facilities that have been advancing OSAM capabilities exist across the country and in space aboard the ISS. This figure presents a summary of several facilities, with Department of Defense and supporting FFRDC facilities in orange, NASA facilities in blue, and academic facilities in green. The authors recognize that this is not an exhaustive list, and any suggestions for additional facilities are welcome using the online survey.

5 CONTRIBUTORS

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6 APPENDIX

This appendix presents more details on the OSAM development activities and technologies that define the current state of OSAM. Table 1 presents all the entries listed in the *OSAM State of Play* and highlights which capability area(s) each is applicable to. Note that many of the entries are applicable to multiple capability areas, and the entries are cross listed where the authors thought applicable and where there is sufficient data. After the table, more information about the use/demonstration date, developing organization, country of origin, and select performance parameters are provided for each entry, organized by capability area.

Table 1: This table lists all the OSAM development activities and technologies in the OSAM State of Play mapped to the applicable capability area(s).

	1. Robotic Manipulation	**2. RPO, Capture, Docking, & Mating**	**3. Relocation**	**4. Planned Repair, Upgrade, Maint., & Install.**	**5. Unplanned or Legacy Repair & Maintenance**	**6. Refueling & Fluid Transfer**	**7. Structural Manufacturing & Assembly**	**8. Recycling, Reuse, & Repurposing**	**9. Parts & Goods Manufacturing**	**10. Surface Construction**	**11. Inspection / Metrology**
3D Printed Habitat Challenge										X	
3D Printing in Zero G TDM									X		
Additive Construction with Mobile Emplacement (ACME)										X	
Additive Manufacturing Facility (AMF)									X		
AeroCube-10		X									
Alpha Magnetic Spectrometer (AMS-02)											X
ANGELS		X									X
Aolong-1		X	X								
Archinaut							X				

	1. Robotic Manipulation	**2. RPO, Capture, Docking, & Mating**	**3. Relocation**	**4. Planned Repair, Upgrade, Maint., & Install.**	**5. Unplanned or Legacy Repair & Maintenance**	**6. Refueling & Fluid Transfer**	**7. Structural Manufacturing & Assembly**	**8. Recycling, Reuse, & Repurposing**	**9. Parts & Goods Manufacturing**	**10. Surface Construction**	**11. Inspection / Metrology**
Argon Autonomous Rendezvous and Docking (AR&D) Sensor		X									
ARMADAS										X	
Assemblers	X						X				
Axon/Dactylus				X							
Beam Fabricator							X				
Bio-memetic Snake Arm Robot											X
Canadarm (Shuttle Remote Manipulator System)	X										
Canadarm2 (Space Station Remote Manipulator System)	X										
Canadarm3	X										
CHAPEA										X	
Dextre	X										
Dog Tag				X							
EASE/Access							X				
End-of-Life Services by Astroscale Demonstration (ELSA-d)		X	X								
Engineering Test Satellite VII	X										
European Robotic Arm (ERA)	X										
Fluid Acquisition & Resupply Experiment I (FARE-I)						X					

	1. Robotic Manipulation	**2. RPO, Capture, Docking, & Mating**	**3. Relocation**	**4. Planned Repair, Upgrade, Maint., & Install.**	**5. Unplanned or Legacy Repair & Maintenance**	**6. Refueling & Fluid Transfer**	**7. Structural Manufacturing & Assembly**	**8. Recycling, Reuse, & Repurposing**	**9. Parts & Goods Manufacturing**	**10. Surface Construction**	**11. Inspection / Metrology**
Fluid Acquisition & Resupply Experiment II (FARE-II)						X					
Furphy Prototype Tanker						X					
FuseBlox				X							
GaLORE Project										X	
GOLD-2 Connector				X							
Hinge for Use in a Tension Stiffened and Tendon Actuated Manipulator							X				
HOTDOCK				X							
Hyper Integrated Satlet (HISat)				X							
iBOSS iSSI				X							
In Situ Construction GCD Project										X	
In-Situ Fabrication and Repair Project (ISFR)										X	
Instrument Deployment Arm (Insight)	X										
Ion			X								
Japanese Experiment Module Remote Manipulator System (JEM-RMS)	X										
Japanese Experiment Module Small Fine Arm	X										

	1. Robotic Manipulation	2. RPO, Capture, Docking, & Mating	3. Relocation	4. Planned Repair, Upgrade, Maint., & Install.	5. Unplanned or Legacy Repair & Maintenance	6. Refueling & Fluid Transfer	7. Structural Manufacturing & Assembly	8. Recycling, Reuse, & Repurposing	9. Parts & Goods Manufacturing	10. Surface Construction	11. Inspection / Metrology
Joint Design Using Electron Beam Welding for Autonomous In-Space Truss Assembly (EBW Joint)							X				
KRAKEN	X										
LANCE										X	
Laura											X
LEO Knight		X			X						
Lightweight Surface Manipulator System (LSMS)	X									X	
Mag Tag				X							
Mars Exploration Rover Robotic Arms	X										
Mars Science Laboratory Robotic Arm	X										
Mars Surveyor 2001 Robotic Arm	X										
Mars Volatiles and Climate Surveyor Robotic Arm (MVACS)	X										
Metal Advanced Manufacturing Bot-Assisted Assembly (MAMBA)								X			
Mission Extension Pods			X		X						

	1. Robotic Manipulation	2. RPO, Capture, Docking, & Mating	3. Relocation	4. Planned Repair, Upgrade, Maint., & Install.	5. Unplanned or Legacy Repair & Maintenance	6. Refueling & Fluid Transfer	7. Structural Manufacturing & Assembly	8. Recycling, Reuse, & Repurposing	9. Parts & Goods Manufacturing	10. Surface Construction	11. Inspection / Metrology
Mission Extension Vehicle (MEV-1)		X	X								
Mission Extension Vehicle 2 (MEV-2)		X	X								
Mission Robotic Vehicle (MRV)		X			X						
MMPACT										X	
Motiv Robotic Arm	X						X				
Multimaterial Fabrication Laboratory									X		
Mycroft		X									X
NASA Docking System (NDS)		X									
NASA Intelligent Jigging and Assembly Robot (NINJAR)							X				
NASA Servicing Arm	X										
NASA STMD 2020 Tipping Point Selections on Cryogenic Fluid Management Technology Demonstration						X					
On-Demand Manufacturing of Electronics (ODME)									X		
Orbital Express		X		X		X					
Orbital Express Demonstration Manipulator System (OEDMS)	X										

	1. Robotic Manipulation	2. RPO, Capture, Docking, & Mating	3. Relocation	4. Planned Repair, Upgrade, Maint., & Install.	5. Unplanned or Legacy Repair & Maintenance	6. Refueling & Fluid Transfer	7. Structural Manufacturing & Assembly	8. Recycling, Reuse, & Repurposing	9. Parts & Goods Manufacturing	10. Surface Construction	11. Inspection / Metrology
Orbital Maneuvering Vehicle (OMV)			X								
Orbital Refueling System (ORS) Flight Demonstration						X					
OSAM-1		X			X	X					
Perseverance Sample Handling Assembly (SHA)	X										
Phoenix Mars Lander Robotic Arm	X										
Precision Assembled Space Structures (PASS)							X				
Programmable Josephson Voltage Standard (PJVS)											X
Progress Vehicle and ATV Refueling of ISS						X					
Ranger	X										
RASSOR										X	
RAVEN		X									
REACT										X	
Recyclable Packaging Materials								X			
Redwire Regolith Print (RegISS)									X	X	
ReFabricator								X			
Robonaut2	X										

	1. Robotic Manipulation	2. RPO, Capture, Docking, & Mating	3. Relocation	4. Planned Repair, Upgrade, Maint., & Install.	5. Unplanned or Legacy Repair & Maintenance	6. Refueling & Fluid Transfer	7. Structural Manufacturing & Assembly	8. Recycling, Reuse, & Repurposing	9. Parts & Goods Manufacturing	10. Surface Construction	11. Inspection / Metrology
Robotic External Leak Locator (RELL)											X
Robotic Refueling Mission (RRM)					X						
Robotic Refueling Mission 3 (RRM3)						X					
Robotic Servicing of Geosynchronous Satellites (RSGS)/Front-end Robotic Enabling Near-term Demonstration (FREND)	X	X									
Robotically Compatible Erectable Joint with Square Cross-Section							X				
Seeker											X
SHEAth-based Rollable Lenticular-Shaped and Low-Stiction (SHEARLESS) Composite Booms							X				
Sherpa-FX			X								
Sherpa-LTC			X								
Sherpa-LTE			X								
Shijian-17		X									

	1. Robotic Manipulation	2. RPO, Capture, Docking, & Mating	3. Relocation	4. Planned Repair, Upgrade, Maint., & Install.	5. Unplanned or Legacy Repair & Maintenance	6. Refueling & Fluid Transfer	7. Structural Manufacturing & Assembly	8. Recycling, Reuse, & Repurposing	9. Parts & Goods Manufacturing	10. Surface Construction	11. Inspection / Metrology
Sintered Inductive Metal Printer with Laser Exposure (SIMPLE)									X		
Sonatest Veo PAUT											X
SOUL		X		X							
Space Infrastructure Dexterous Robot (SPIDER)	X						X				
Space Utility Vehicle (SUV)			X								
Standard Interface for Robotic Manipulation of Payloads in Future Space Missions (SIROM)				X							
Storage Fluid Management Demonstration (SFMD)						X					
Strela Cargo Cranes	X										
Structural Joint with Multi-Axis Load Carrying Capability							X				
Strut Attachment, Manipulation, and Utility Robotic Aide (SAMURAI)							X				
Superfluid Helium On-Orbit Transfer (SHOOT) Flight Demonstration						X					
Tailored Universal Feedstock for Forming (TuFF) Reformability Demo								X			

	1. Robotic Manipulation	**2. RPO, Capture, Docking, & Mating**	**3. Relocation**	**4. Planned Repair, Upgrade, Maint., & Install.**	**5. Unplanned or Legacy Repair & Maintenance**	**6. Refueling & Fluid Transfer**	**7. Structural Manufacturing & Assembly**	**8. Recycling, Reuse, & Repurposing**	**9. Parts & Goods Manufacturing**	**10. Surface Construction**	**11. Inspection / Metrology**
TALISMAN	X										
Tanker-001 Tenzing		X				X					
The Puck & Service Pods				X							
Thermally Reversible Polymers for AM Feedstock								X			
Tianyuan 1 refueling demonstration						X					
Vigoride		X	X								
Visual Inspection Poseable Invertebrate Robot (VIPIR)											X
Vulcan									X		
XSS-10		X									X
XSS-11		X									X

6.1 ROBOTIC MANIPULATION

6.1.1 RM - 1: Assemblers

Description: Collective project goal of increasing the TRL for modular robots, autonomous in-space assembly, and to develop a robotic prototype for ground testing. To reach the goal of the project both new hardware and software is being developed.

Developer: NASA LaRC
Country: USA
First Use Date: TBD
Status: Development

Performance Parameters:
Reach(m): Unavailable
Degrees of Freedom: Unavailable
Grapple Type: Unavailable

6.1.2 RM - 2: Canadarm (Shuttle Remote Manipulator System)

Description: Canadarm or Canadarm1 (officially Shuttle Remote Manipulator System or SRMS) is a series of robotic arms that were used on the Space Shuttle orbiters to deploy, maneuver, and capture payloads. After the Space Shuttle Columbia disaster, the Canadarm was always paired with the Orbiter Boom Sensor System (OBSS), which was used to inspect the exterior of the Shuttle for damage to the thermal protection system.

Developer: Spar Aerospace
Country: Canada
First Use Date: 1981
Status: Flown

Performance Parameters:
Reach(m): 15
Degrees of Freedom: 8
Grapple Type: Snare End Effector

6.1.3 RM - 3: Canadarm2 (Space Station Remote Manipulator System)

Description: Officially known as the Space Station Remote Manipulator System (SSRMS). Launched on STS-100 in April 2001, this second-generation arm is a larger, more advanced version of the Space Shuttle's original Canadarm.

Developer: CSA/MDA
Country: Canada
First Use Date: 2001
Status: Flown

Performance Parameters:
Reach(m): 17.6
Degrees of Freedom: 7
Grapple Type: Snare End Effector; Latches; Umbilicals

6.1.4 RM - 4: Canadarm3

Description: This smaller Canadarm3 will be used for berthing the modules and inspecting the Lunar Gateway. The Canadarm3, a robotic remote manipulator arm, similar to the Space Shuttle Canadarm and International Space Station Canadarm2. The arm is to be the contribution of the Canadian Space Agency (CSA) to this international endeavor. CSA contracted MDA (MacDonald, Dettwiler and Associates) to build the arm. MDA previously built Canadarm2, while its former subsidiary, Spar Aerospace, built Canadarm.

Developer:	CSA/MDA	**Country:**	Canada
First Use Date:	2024	**Status:**	Development

Performance Parameters:

Reach(m):	8.5
Degrees of Freedom:	7
Grapple Type:	Unavailable

6.1.5 RM - 5: Dextre

Description: The Special Purpose Dexterous Manipulator, or "Dextre", is a smaller two-armed robot that can attach to Canadarm2, the ISS or the Mobile Base System. The arms and its power tools are capable of handling the delicate assembly tasks and changing Orbital Replacement Units (ORUs) currently handled by astronauts during space walks. Although Canadarm2 can move around the station in an "inchworm motion", it's unable to carry anything with it unless Dextre is attached.

Developer:	CSA/MDA	**Country:**	Canada
First Use Date:	2008	**Status:**	Flown

Performance Parameters:

Reach(m):	3.35
Degrees of Freedom:	7
Grapple Type:	Latching End Effector; Robotic Micro Conical Tools; RMM Tools

6.1.6 RM - 6: Engineering Test Satellite VII

Description: ETSVII (Japanese nickname: Kiku7) is a JAXA (formerly NASDA) technology demonstration satellite. The overall mission objectives are to conduct space robotic experiments and to demonstrate its utility for unmanned orbital operation and servicing tasks rendezvous-docking techniques).

Developer:	NASDA (now JAXA)	**Country:**	Japan
First Use Date:	1998	**Status:**	Flown

Performance Parameters:

Reach(m):	2
Degrees of Freedom:	6
Grapple Type:	Grapple

6.1.7 RM - 7: European Robotic Arm (ERA)

Description: The European Robotic Arm (ERA) works with the new Russian airlock, to transfer small payloads directly from inside to outside the International Space Station. This will reduce the setup time for astronauts on a spacewalk and allow ERA to work alongside astronauts.

Developer:	Dutch Space	**Country:**	Multiple (Europe)
First Use Date:	2021	**Status:**	Flown

Performance Parameters:

Reach(m):	11.3
Degrees of Freedom:	7
Grapple Type:	Grapple; Integrated Tools

6.1.8 RM - 8: Instrument Deployment Arm (Insight)

Description: The IDA originated as the robotic arm built for the Jet Propulsion Laboratory (JPL) for the cancelled Mars 2001 Surveyor mission in 1998.

Developer:	Maxar/MDA	**Country:**	USA
First Use Date:	2016	**Status:**	Flown

Performance Parameters:

Reach(m):	1.9
Degrees of Freedom:	4
Grapple Type:	Scoop; Grapple; Camera

6.1.9 RM - 9: Japanese Experiment Module Remote Manipulator System (JEM-RMS)

Description: Kibo's robotic arm, Japanese Experiment Module Remote Manipulator System (JEMRS), is a robotic manipulator system intended for supporting experiments to be conducted on Kibo's Exposed Facility or for supporting Kibo's maintenance tasks.

Developer:	JAXA	**Country:**	Japan
First Use Date:	2008	**Status:**	Flown

Performance Parameters:

Reach(m):	10
Degrees of Freedom:	6
Grapple Type:	Grapple; JEM SFA Connection

6.1.10 RM - 10: Japanese Experiment Module Small Fine Arm

Description: The Small Fine Arm (SFA) consists of some electronics, booms, joints, and effectors called "tools," and TV cameras. The SFA will be attached to the end of the Main Arm when operated.

Developer:	JAXA	**Country:**	Japan
First Use Date:	2008	**Status:**	Flown

Performance Parameters:

Reach(m):	2.2
Degrees of Freedom:	6
Grapple Type:	3 Fingers; Torque Driver; Electric Connectors

6.1.11 RM - 11: KRAKEN

Description: TUI has developed the KRAKEN robotic arm to provide the space industry with a compact, high-performance, and cost-effective manipulator to enable small spacecraft to perform in-space assembly, manufacturing, and servicing missions.

Developer:	Tethers Unlimited Inc.	**Country:**	USA
First Use Date:	TBD	**Status:**	Development

Performance Parameters:

Reach(m):	Various
Degrees of Freedom:	7
Grapple Type:	Swappable; Tool-Change Interface; Power/Data Interface

6.1.12 RM - 12: Lightweight Surface Manipulator System (LSMS)

Description: The Lightweight Surface Manipulation System allows for fine positioning of a payload in both the translational and rotational directions. Attachments include buckets, pallet forks, grappling devices, sensors, and robotic arms.

Developer:	NASA LaRC	**Country:**	USA
First Use Date:	0	**Status:**	Development

Performance Parameters:

Reach(m):	Scalable
Degrees of Freedom:	Unavailable
Grapple Type:	Unavailable

6.1.13 RM - 13: Mars Exploration Rover Robotic Arms

Description: The Instrument Deployment Device (IDD) is a five degree-of-freedom robotic arm designed to give the Mars Exploration Rover (MER) the ability to gain physical access to the rocks and soil in the Martian environment. The IDD will accurately position each of four separate instruments attached to its end effector against and near geological specimens selected for scientific investigation.

Developer:	NASA/Maxar/MDA	**Country:**	USA
First Use Date:	2004	**Status:**	Flown

Performance Parameters:

Reach(m):	1
Degrees of Freedom:	5
Grapple Type:	Abrasion Tool; Spectrometer; Camera

6.1.14 RM - 14: Mars Science Laboratory Robotic Arm

Description: The Mars Science Laboratory mission is NASA’s most ambitious science mission to another planet. MSL incorporates many lessons learned from the Pathfinder mission and Sojourner rover, the twin Mars Exploration Rovers, and the Phoenix Lander.

Developer:	Maxar/MDA	**Country:**	USA
First Use Date:	2012	**Status:**	Flown

Performance Parameters:

Reach(m):	2.2
Degrees of Freedom:	5
Grapple Type:	5 Scientific Instruments; Drill

6.1.15 RM - 15: Mars Surveyor 2001 Robotic Arm

Description: The Mars Surveyor 2001 Lander will [was scheduled to] carry with it both a Robotic Arm and Rover to support various science and technology experiments. The Marie Curie Rover, the twin sister to Sojourner Truth, is expected to explore the surface of Mars in early 2002.

Developer:	NASA JPL	**Country:**	USA
First Use Date:	2001	**Status:**	Cancelled

Performance Parameters:

Reach(m):	2
Degrees of Freedom:	4
Grapple Type:	Scoop; Scraping Blades; Electrometer

6.1.16 RM - 16: Mars Volatiles and Climate Surveyor Robotic Arm (MVACS)

Description: The primary purpose of the MVACS Robotic Arm is t support the other MVACS science instruments by digging trenches in the Marian soil, acquiring and dumping soil samples in to the Thermal Evolved Gas Analyzer, and other support functions.

Developer:	NASA/Univ of Arizona	**Country:**	USA
First Use Date:	1999	**Status:**	Crashed

Performance Parameters:

Reach(m):	2.2
Degrees of Freedom:	4
Grapple Type:	Scoop; Temp probe; Camera

6.1.17 RM - 17: Motiv Robotic Arm

Description: The technology demonstration, previously called Archinaut One, will build, assemble, and deploy its own operational solar array.

Developer:	NASA, Made in Space, Northrop Grumman, JPL	**Country:**	USA
First Use Date:	TBD	**Status:**	Development

Performance Parameters:

Reach(m):	1-3
Degrees of Freedom:	4-7
Grapple Type:	Unavailable

6.1.18 RM - 18: NASA Servicing Arm

Description: The Robotic Servicing Arm has extensive heritage from arms used in past Mars rover missions. The system design heavily leverages the flight-qualified robotic arm developed for Defense Advanced Research Projects Agency (DARPA)'s Spacecraft for the Universal Modification of Orbits and Front-end Robotics Enabling Near-term Demonstration (FREND) programs in the mid-2000s. It builds off of previous NASA and DARPA investments in motion control, robotic software frameworks, flex harnesses, force-torque sensor, joint design, and flight operations experience.

Developer:	NASA	**Country:**	USA
First Use Date:	TBD	**Status:**	Development

Performance Parameters:

Reach(m):	2.46
Degrees of Freedom:	7
Grapple Type:	Six-Axis Force/Torque Sensor

6.1.19 RM - 19: Orbital Express Demonstration Manipulator System (OEDMS)

Description: Using a robotic arm on-orbit, the Orbital Express mission demonstrated autonomous capture of a fully unconstrained free-flying client satellite, autonomous transfer of a functional battery On-Orbit Replaceable Unit (ORU) between two spacecraft, and autonomous transfer of a functional computer ORU.

Developer:	DARPA/MDA	**Country:**	USA
First Use Date:	2007	**Status:**	Flown

Performance Parameters:

Reach(m):	2.8
Degrees of Freedom:	6
Grapple Type:	Mouse Trap; Cone; Probe

6.1.20 RM - 20: Perseverance Sample Handling Assembly (SHA)

Description: The 7-foot-long robotic arm on Perseverance can move a lot like yours. It has a shoulder, elbow, and writs "joints" for maximum flexibility. The arm lets the rover work as a human geologist would: by holding and using science tools with its "hand" or turret.

Developer:	Maxar/MDA	**Country:**	USA
First Use Date:	2020	**Status:**	Flown

Performance Parameters:

Reach(m):	2.1
Degrees of Freedom:	5
Grapple Type:	Tool Turret; SHERLOC; WATSON; PIXL; GDRT; Drill

6.1.21 RM - 21: Phoenix Mars Lander Robotic Arm

Description: The RA was an essential system for achieving the scientific goals of the Phoenix mission by providing support to the other science instruments as well as conducting specific soil mechanics experiments.

Developer:	Maxar/MDA	**Country:**	USA
First Use Date:	2008	**Status:**	Flown

Performance Parameters:

Reach(m):	2
Degrees of Freedom:	4
Grapple Type:	Scoop; Camera

6.1.22 RM - 22: Ranger

Description: First use of robot control of "hazardous" payload, leveraged by Robonaut and Restore.

Developer:	UMD Space Systems Laboratory	**Country:**	USA
First Use Date:	1995	**Status:**	Flight Qual

Performance Parameters:

Reach(m):	1.35
Degrees of Freedom:	8
Grapple Type:	Bolt & Angle Drives; Jaw gripper

6.1.23 RM - 23: Robonaut2

Description: Robonaut 2, or R2, was developed jointly by NASA and General Motors under a cooperative agreement to develop a robotic assistant that can work alongside humans, whether they are astronauts in space or workers at GM manufacturing plants on Earth.

Developer:	NASA/General Motors	**Country:**	USA
First Use Date:	1999	**Status:**	Flown

Performance Parameters:

Reach(m):	0.812
Degrees of Freedom:	42
Grapple Type:	12-DOF Hands

6.1.24 RM - 24: Robotic Servicing of Geosynchronous Satellites (RSGS)/Front-end Robotic Enabling Near-term Demonstration (FREND)

Description: The FREND robotic arm was developed by DARPA to demonstrate a seven degree-of-freedom arm capable of autonomous grapple and manipulation. The design is being leveraged by OSAM-1/Restore-L and RSGS.

Developer:	DARPA/NRL	**Country:**	USA
First Use Date:	2007	**Status:**	Flight Qual

Performance Parameters:

Reach(m):	1.8
Degrees of Freedom:	7
Grapple Type:	Grapple

6.1.25 RM - 25: Space Infrastructure Dexterous Robot (SPIDER)

Description: The OSAM-1 spacecraft will include an attached payload called Space Infrastructure Dexterous Robot (SPIDER). SPIDER includes a lightweight 16-foot (5-meter) robotic arm, bringing the total number of robotic arms flying on OSAM-1 to three. Previously known as Dragonfly during the ground demonstration phase of the NASA Tipping Point partnership, SPIDER will assemble seven elements to form a functional 9-foot (3-meter) communications antenna.

Developer:	Maxar	**Country:**	USA
First Use Date:	TBD	**Status:**	Development

Performance Parameters:

Reach(m):	5
Degrees of Freedom:	7
Grapple Type:	MDA provided dexterous end effector

6.1.26 RM - 26: Strela Cargo Cranes

Description: Strela is a class of four Russian built cargo cranes used during EVAs to move cosmonauts and components around the exterior of the Soviet/Russian space station Mir and the Russian Orbital Segment of the International Space Station. Both telescoping booms extend like fishing rods and are used to move massive components outside the station.

Developer:	Russia	**Country:**	Russia
First Use Date:	1986	**Status:**	Flown

Performance Parameters:

Reach(m):	14
Degrees of Freedom:	Unavailable
Grapple Type:	Unavailable

6.1.27 RM - 27: TALISMAN

Description: The Tendon-Actuated Lightweight In-Space MANipulator is a long reach manipulator arm that can be used for satellite servicing, small payload delivery, and large space observatory assembly.

Developer:	NASA LaRC	**Country:**	USA
First Use Date:	TBD	**Status:**	Development

Performance Parameters:

Reach(m):	20
Degrees of Freedom:	5
Grapple Type:	Swappable end effector

6.2 RPO, CAPTURE, DOCKING, AND MATING

6.2.1 RCDM - 1: AeroCube-10

Description: Pair of 1.5U CubeSats (one with 28 deployable atmospheric probes and laser beacon, another with camera and propulsion system). AC-10B entered "orbit" around AC-10A and used on-board camera to take resolved images of AC-10A. AC-10B took photos from 22 meters away.

Developer:	The Aerospace Corporation	**Country:**	United States
First Use Date:	2019	**Status:**	Flown

Performance Parameters:

Contact v. Non-contact:	Non-Contact
Misalign. Tolerance:	N/A
Max RPO (m):	Unavailable
Cooperative v. Non-Cooperative:	Unavailable

6.2.2 RCDM - 2: ANGELS

Description: Automated Navigation and Guidance Experiment for Local Space evaluates SSA techniques in region around its Delta-4 launch vehicle upper stage. Beginning experiments approximately 50 km away from the upper stage and progressing to within several kilometers. Uses ground commanded authorization to proceed points throughout the experiment.

Developer:	AFRL	**Country:**	United States
First Use Date:	2014	**Status:**	Flown

Performance Parameters:

Contact v. Non-contact:	Non-Contact
Misalign. Tolerance:	N/A
Max RPO (m):	50000
Cooperative v. Non-Cooperative:	Non-cooperative

6.2.3 RCDM - 3: Aolong-1

Description: Tested satellite with robotic arm grappling for small debris removal.

Developer:	NUDT/PLA	**Country:**	China
First Use Date:	2016	**Status:**	Flown

Performance Parameters:

Contact v. Non-contact:	Contact
Misalign. Tolerance:	Unavailable
Max RPO (m):	Unavailable
Cooperative v. Non-Cooperative:	Non-cooperative

6.2.4 RCDM - 4: Argon Autonomous Rendezvous and Docking (AR&D) Sensor

Description: Argon integrated essential RPO components and unique algorithms into a system that autonomously imaged, visually captured and tracked dynamic and static targets. Demonstrations at various ranges tested the components' capabilities and ensured that the system smoothly transitioned among each simulated servicing-mission phase.

Developer:	NASA GSFC	**Country:**	USA
First Use Date:	0	**Status:**	Completed, upgraded to RAVEN

Performance Parameters:

Contact v. Non-contact:	Non-Contact
Misalign. Tolerance:	N/A
Max RPO (m):	90
Coop. v. Non-Coop:	Non-cooperative

6.2.5 RCDM - 5: End-of-Life Services by Astroscale Demonstration (ELSA-d)

Description: Consists of two spacecraft (servicer and client) to demonstrate core technologies for debris docking and removal. Servicer will repeatedly release and dock with the client using a ferromagnetic plate.

Developer:	Astroscale	**Country:**	Japan
First Use Date:	Unlisted	**Status:**	Flown (to be tested)

Performance Parameters:

Contact v. Non-contact:	Contact
Misalign. Tolerance:	Unavailable
Max RPO (m):	Unavailable
Coop. v. Non-Coop:	Both

6.2.6 RCDM - 6: ETS-VII

Description: ETSVII (Japanese nickname: Kiku7) is a JAXA (formerly NASDA) technology demonstration satellite. The overall mission objectives are to conduct space robotic experiments and to demonstrate its utility for unmanned orbital operation and servicing tasks rendezvous-docking techniques).

Developer:	JAXA	**Country:**	USA
First Use Date:	1998	**Status:**	Flown

Performance Parameters:

Contact v. Non-contact:	Contact
Misalign. Tolerance:	1.3mm arm tolerance
Max RPO (m):	10000
Coop. v. Non-Coop:	Cooperative

6.2.7 RCDM - 7: LEO Knight

Description: LEO Knight will provide the capability to assemble ESPA-class modules together to form persistent space platforms, capture space debris and transport it to recycling hubs, and refuel and repair small satellites.

Developer: Tethers Unlimited **Country:** United States
First Use Date: TBD **Status:** Development

Performance Parameters:
Contact v. Non-contact: Contact
Misalign. Tolerance: Unavailable
Max RPO (m): Unavailable
Coop. v. Non-Coop: Cooperative

6.2.8 RCDM - 8: Mission Extension Vehicle (MEV-1)

Description: MEV is the industry's first satellite life extension vehicle, designed to dock to geostationary satellites whose fuel is nearly depleted. Once connected to its client satellite, MEV uses its own thrusters and fuel supply to extend the satellite's lifetime. When the customer no longer desires MEV's service, the spacecraft will undock and move on to the next client satellite.

Developer: Northrop Grumman **Country:** United States
First Use Date: 2019 **Status:** Flown

Performance Parameters:
Contact v. Non-contact: Contact
Misalign. Tolerance: Unavailable
Max RPO (m): 80
Coop. v. Non-Coop: Cooperative

6.2.9 RCDM - 9: Mission Extension Vehicle 2 (MEV-2)

Description: MEV is the industry's first satellite life extension vehicle, designed to dock to geostationary satellites whose fuel is nearly depleted. Once connected to its client satellite, MEV uses its own thrusters and fuel supply to extend the satellite's lifetime. When the customer no longer desires MEV's service, the spacecraft will undock and move on to the next client satellite.

Developer: Northrop Grumman **Country:** United States
First Use Date: 2021 **Status:** Flown

Performance Parameters:
Contact v. Non-contact: Contact
Misalign. Tolerance: Unavailable
Max RPO (m): Unavailable
Coop. v. Non-Coop: Cooperative

6.2.10 RCDM - 10: Mission Robotic Vehicle (MRV)

Description: A future on-orbit servicing bus developed from the Mission Extension Vehicle. The robotic payload will be supplied by DARPA and developed by the US Naval Research Institute.

Developer:	Northrup Grumman	**Country:**	United States
First Use Date:	TBD	**Status:**	Development

Performance Parameters:

Contact v. Non-contact:	Contact
Misalign. Tolerance:	Unavailable
Max RPO (m):	Unavailable
Coop. v. Non-Coop:	Both

6.2.11 RCDM - 11: Mycroft

Description: 4th generational experimental SSA spacecraft that builds upon technology, knowledge, and lessons learned from XSS-10, XSS-11, and ANGELS. Evaluates region around EAGLE using SSA camera and uses sensors and software to perform advanced GNC functions. Exploring ways to enhance space object characterization.

Developer:	AFRL	**Country:**	United States
First Use Date:	2018	**Status:**	Flown

Performance Parameters:

Contact v. Non-contact:	Non-Contact
Misalign. Tolerance:	Unavailable
Max RPO (m):	3500
Coop. v. Non-Coop:	Unavailable

6.2.12 RCDM - 12: NASA Docking System (NDS)

Description: Allows visiting vehicles to dock to ISS. Uses International Docking System Standard.

Developer:	NASA	**Country:**	United States
First Use Date:	2018	**Status:**	Flown

Performance Parameters:

Contact v. Non-contact:	Contact
Misalign. Tolerance:	0.1 m, 5 degrees in one axis
Max RPO (m):	Unavailable
Coop. v. Non-Coop:	Cooperative

6.2.13 RCDM - 13: Orbital Express

Description: Launched March 8, 2007 as part of the United States Air Force SpaceTest Program (STP), Orbital Express demonstrated automated rendezvous and capture of two spacecraft (ASTRO and NEXTSat), transfer of propellant, and transfer of a modular spacecraft component. Flow sensors demonstrated 5-10 percent flow rate error on N2H4 transfer with no significant issues. The mission demonstrated 9 mate/demate cycles on orbit and demonstrated robotic Orbital Replacement Unit (ORU) transfer and installation.

Developer:	DARPA, NASA	**Country:**	United States
First Use Date:	2007	**Status:**	Flown

Performance Parameters:

Contact v. Non-contact:	Contact
Misalign. Tolerance:	5 degrees +/-
Max RPO (m):	1000000
Coop. v. Non-Coop:	Cooperative

6.2.14 RCDM - 14: OSAM-1

Description: OSAM-1 is a robotic spacecraft equipped with the tools, technologies and techniques needed to extend satellites' lifespans - even if they were not designed to be serviced on orbit. During its mission, the OSAM-1 servicer will rendezvous with, grasp, refuel and relocate a government-owned satellite to extend its life. OSAM-1's capabilities can give satellite operators new ways to manage their fleets more efficiently and derive more value from their initial investment. These capabilities could even help mitigate the looming problem of orbital debris. OSAM-1 will also be able to assemble a communications antenna and manufacture a beam on orbit.

Developer:	NASA/Maxar	**Country:**	United States
First Use Date:	TBD	**Status:**	Development

Performance Parameters:

Contact v. Non-contact:	Contact
Misalign. Tolerance:	Unavailable
Max RPO (m):	Unavailable
Coop. v. Non-Coop:	Non-cooperative

6.2.15 RCDM - 15: RAVEN

Description: Raven is a technology-filled module on the International Space Station that will help NASA test key elements of a new spacecraft autopilot system. Through Raven, NASA will be one step closer to having a relative navigation capability that it can take "off the shelf" and use with minimum modifications for many missions—for decades to come.

Developer:	NASA GSFC	**Country:**	USA
First Use Date:	N/A	**Status:**	Flown

Performance Parameters:

Contact v. Non-contact:	Non-Contact
Misalign. Tolerance:	N/A
Max RPO (m):	100
Coop. v. Non-Coop:	Both

6.2.16 RCDM - 16: Robotic Servicing of Geosynchronous Satellites (RSGS)/Front-end Robotic Enabling Near-term Demonstration (FREND)

Description: First demo for autonomous capture; leveraged by Restore. Two FREND arms are expected to be used in DARPA's Phoenix Project.

Developer:	DARPA/NRL	**Country:**	USA
First Use Date:	2007	**Status:**	Flight Qual

Performance Parameters:

Contact v. Non-contact:	Contact
Misalign. Tolerance:	Unavailable
Max RPO (m):	Unavailable
Coop. v. Non-Coop:	Cooperative

6.2.17 RCDM - 17: Shijian-17

Description: Conducted a series of space rendezvous and proximity operations in geosynchronous orbit.

Developer:	China Academy of Space Technology (CAST)	**Country:**	China
First Use Date:	2016	**Status:**	Flown

Performance Parameters:

Contact v. Non-contact:	Non-Contact
Misalign. Tolerance:	N/A
Max RPO (m):	N/A
Coop. v. Non-Coop:	N/A

6.2.18 RCDM - 18: SOUL

Description: SOUL is a tethered robotic spacecraft that is designed to provide self-inspection and self-servicing. SOUL is a small (<10kg) robotic, self-propelled, self-navigating, autonomous vehicle that is equipped with a tool and that receives power & commands from the host spacecraft. It replaces a robotic arm and has the advantage of infinite degrees of freedom.

Developer:	Busek Co., Inc.	**Country:**	United States
First Use Date:	TBD	**Status:**	Phase II testing

Performance Parameters:

Contact v. Non-contact:	Contact
Misalign. Tolerance:	Unavailable
Max RPO (m):	30
Coop. v. Non-Coop:	Both

6.2.19 RCDM - 19: Tanker-001 Tenzing

Description: Operational fuel depot storing green propellant High-Test Peroxide. Contains the RAFTI service valve for fill/drain. High and low-pressure variants of RAFTI compatible with common propellants. Space Coupling Half (other side of Service Valve) supports both primary docking and secondary attachment of two spacecraft.

Developer:	OrbitFab	**Country:**	United States
First Use Date:	Launched 6/30/2021	**Status:**	Flown

Performance Parameters:

Contact v. Non-contact:	Contact
Misalign. Tolerance:	Not given, stated "significant" misalignment tolerance
Max RPO (m):	N/A
Coop. v. Non-Coop:	Cooperative

6.2.20 RCDM - 20: Vigoride

Description: Space tug designed for orbital plane changes, inclination adjustments, and payload delivery.

Developer:	Momentus	**Country:**	United States
First Use Date:	TBD	**Status:**	Development

Performance Parameters:

Contact v. Non-contact:	Contact
Misalign. Tolerance:	Unavailable
Max RPO (m):	Unavailable
Coop. v. Non-Coop:	Unavailable

6.2.21 RCDM - 21: XSS-10

Description: Micro-satellite with objectives to demonstrate autonomous navigation, proximity operations, and inspection of another space object.

Developer:	AFRL	**Country:**	United States
First Use Date:	2003	**Status:**	Flown

Performance Parameters:

Contact v. Non-contact:	Non-Contact
Misalign. Tolerance:	N/A
Max RPO (m):	Unavailable
Coop. v. Non-Coop:	Non-cooperative

6.2.22 RCDM - 22: XSS-11

Description: Micro-satellite demonstrating rendezvous and proximity operations with expended rocket body. Conducting proximity maneuvers with several US-owned, dead, or inactive resident space objects near its orbit.

Developer:	AFRL	**Country:**	United States
First Use Date:	2005	**Status:**	Flown

Performance Parameters:

Contact v. Non-contact:	Non-Contact
Misalign. Tolerance:	N/A
Max RPO (m):	5000
Coop. v. Non-Coop:	Non-cooperative

6.3 RELOCATION

6.3.1 R - 1: Aolong-1

Description: Tested satellite robotic arm grappling for small debris removal.

Developer: NUDT/PLA **Country:** China
First Use Date: 2016 **Status:** Flown

Performance Parameters:
Intended Transit: Debris to atmosphere for removal (assumed)
Max. Client Mass: Unavailable
Thruster / Propellant Type: Unavailable

6.3.2 R - 2: End-of-Life Services by Astroscale Demonstration (ELSA-d)

Description: Consists of two spacecraft (servicer and client) to demonstrate core technologies for debris docking and removal. Servicer will repeatedly release and dock with the client using a ferromagnetic plate.

Developer: Astroscale **Country:** Japan
First Use Date: Unlisted **Status:** Flown (to be tested)

Performance Parameters:
Intended Transit: Debris removal
Max. Client Mass: 20 kg
Thruster / Propellant Type: Green chemical

6.3.3 R - 3: Ion

Description: 64U satellite dispenser satellite platform which can deliver to a range of different sized payloads to LEO. The satellite is able to perform orbital maneuvers between payload deployments.

Developer: dSpace **Country:** Italy
First Use Date: 2020 **Status:** Flown

Performance Parameters:
Intended Transit: Altitude and Inclination changes, True anomaly phasing, RAAN shift
Max. Client Mass: 160 kg
Thruster / Propellant Type: Unavailable

6.3.4 R - 4: Mission Extension Pods

Description: Mission extension pods are Northrop's next generation of servicing vehicles. They will be smaller and less expensive life extension service that only performs orbit control, providing up to six years of life extension. They will be installed by a Mission Robotic Vehicle which can carry several pods.

Developer:	Northrup Grumman	**Country:**	United States
First Use Date:	TBD	**Status:**	Development

Performance Parameters:

Intended Transit:	Attitude control of client in GEO
Max. Client Mass:	Unavailable
Thruster / Propellant Type:	Electric

6.3.5 R - 5: Mission Extension Vehicle (MEV-1)

Description: MEV is the industry's first satellite life extension vehicle, designed to dock to geostationary satellites whose fuel is nearly depleted. Once connected to its client satellite, MEV uses its own thrusters and fuel supply to extend the satellite's lifetime. When the customer no longer desires MEV's service, the spacecraft will undock and move on to the next client satellite.

Developer:	Northrop Grumman	**Country:**	United States
First Use Date:	2019	**Status:**	Flown

Performance Parameters:

Intended Transit:	To GEO client to stay in GEO until no longer wanted
Max. Client Mass:	Unavailable
Thruster / Propellant Type:	Electric

6.3.6 R - 6: Mission Extension Vehicle 2 (MEV-2)

Description: MEV-2 is the second Mission Extension Vehicle supplied by Space Logistics LLC, a wholly owned subsidiary of Northrop Grumman. The goal of MEV-2 is to dock to satellites whose fuel is nearly depleted and refuel them on orbit to extend their life. MEV-2 will provide five years of service to its current client satellite before undocking and moving on to provide services for a new mission.

Developer:	Northrop Grumman	**Country:**	United States
First Use Date:	2021	**Status:**	Flown

Performance Parameters:

Intended Transit:	To GEO client to stay in GEO until no longer wanted
Max. Client Mass:	Unavailable
Thruster / Propellant Type:	Electric

6.3.7 R - 7: Orbital Maneuvering Vehicle (OMV)

Description: ESPA based space tug used for orbital relocation for secondary payloads. Offer a variety of sizes and configurations. Aims to perform orbital adjustments and insertions in LEO and GEO.

Developer:	MOOG	**Country:**	United States
First Use Date:	TBD	**Status:**	Development

Performance Parameters:

Intended Transit:	Orbit raising and lowering, plane changes, phasing
Max. Client Mass:	Assorted
Thruster / Propellant Type:	Green, hydrazine

6.3.8 R - 8: Sherpa-FX

Description: 24" ESPA-class deployment system which is capable of deploying multiple payloads at different times.

Developer:	Spaceflight	**Country:**	United States
First Use Date:	2021	**Status:**	Flown

Performance Parameters:

Intended Transit:	Separation from flight vehicle
Max. Client Mass:	Unavailable
Thruster / Propellant Type:	Unavailable

6.3.9 R - 9: Sherpa-LTC

Description: 24" ESPA-class deployment system which is capable of deploying multiple payloads at different times.

Developer:	Spaceflight	**Country:**	United States
First Use Date:	Expected 2021	**Status:**	Planned Flight

Performance Parameters:

Intended Transit:	Orbit raising and lowering, in-plane phasing
Max. Client Mass:	Unavailable
Thruster / Propellant Type:	Bi-propellant, green propulsion, Chemical Propulsion

6.3.10 R - 10: Sherpa-LTE

Description: 24" ESPA-class deployment system which is capable of deploying multiple payloads at different times.

Developer:	Spaceflight	**Country:**	United States
First Use Date:	2021	**Status:**	Flown

Performance Parameters:

Intended Transit:	LTAN and plane changes
Max. Client Mass:	Unavailable
Thruster / Propellant Type:	Electric Propulsion, Xenon propellant

6.3.11 R - 11: Space Utility Vehicle (SUV)

Description: ESPA based Electric space tug system designed to launch with Firefly Aerospace Alpha launch vehicle. Designed for orbital insertion in LEO, GEO, and possible cislunar. Can perform station keeping and can serve as a payload bus.

Developer:	Firefly Aerospace	**Country:**	United States
First Use Date:	TBD	**Status:**	Development

Performance Parameters:

Intended Transit:	Orbit raising and deraising, plane changes, phasing
Max. Client Mass:	800 kg
Thruster / Propellant Type:	Solar-electric

6.3.12 R - 12: Vigoride

Description: Space tug designed for orbital plane changes, inclination adjustments, and payload delivery.

Developer:	Momentus	**Country:**	United States
First Use Date:	TBD	**Status:**	Development

Performance Parameters:

Intended Transit:	Orbit raising and deraising mainly in LEO
Max. Client Mass:	500 kg
Thruster / Propellant Type:	Water plasma engines

6.4 PLANNED REPAIR, UPGRADE, MAINTENANCE, AND INSTALLATION

6.4.1 PRUMI - 1: Axon/Dactylus

Description: Mechanical/electrical/data connecter with active and passive sides for in-space assembly and servicing.

Developer:	Tethers Unlimited	**Country:**	United States
First Use Date:	Unknown	**Status:**	Development

Performance Parameters:
Operation Type: Modular Interface
ORU SWaP: Unavailable
Standard Interface Type: Unavailable

6.4.2 PRUMI - 2: Dog Tag

Description: Mechanical grapple fixture with fiducials that is compatible with magnetic, electroadhesive, geckogrip, or mechanical pinch grasping. Product deployed in space on OneWeb satellites.

Developer:	Altius Space Machines	**Country:**	United States
First Use Date:	2021	**Status:**	Flown

Performance Parameters:
Operation Type: Grapple interface
ORU SWaP: Unavailable
Standard Interface Type: Mechanical

6.4.3 PRUMI - 3: FuseBlox

Description: Androgynous interface for mechanical, electrical, and data. Received Phase II SBIR funding from AFRL.

Developer:	SpaceWorks	**Country:**	United States
First Use Date:	Unavailable	**Status:**	Development

Performance Parameters:
Operation Type: Modular Interface
ORU SWaP: Max Lateral load: Unavailable
Power: 1.1kW
Data Rate: MIL-STD-1553/Gigabit Ethernet
Standard Interface Type: Mechanical, Electrical, Data

6.4.4 PRUMI - 4: GOLD-2 Connector

Description: General purpose latching device suitable for mechanically connecting to 454 kg payload with power and data connections. Options available for custom fluid connection. Passive and active sides.

Developer:	Oceaneering
Country:	United States
First Use Date:	Bartolomeo Module added to ISS in July 2020
Status:	Flown

Performance Parameters:

Operation Type:	Modular Interface
ORU SWaP:	Max Lateral load: Unknown, sized for 125kg nominal ops Power: Up to 800W Data Rate: up to 1Mb/s downlink Heat: Not Available
Standard Interface Type:	Mechanical, Power, Data

6.4.5 PRUMI - 5: HOTDOCK

Description: An androgynous standard interface supporting mechanical, electrical, data, and (optionally) thermal interconnect. Used especially for robotic arm interfacing. The MOSAR-WM walking robotic arm developed by SAS and DLR uses this as the standard interface

Developer:	Space Application Services	**Country:**	Belgium
First Use Date:	July 2021 Final MOSAR Demo	**Status:**	Development (not yet flown)

Performance Parameters:

Operation Type:	Modular Interface
ORU SWaP:	Max Lateral load: 600Nm Power: 4kW Data Rate: Spacewire/Ethernet Heat: 20-50W
Standard Interface Type:	Mechanical, Power, Data, Thermal

6.4.6 PRUMI - 6: Hyper Integrated Satlet (HISat)

Description: Satlets possess the functional capabilities of a traditional spacecraft and are designed to collaboratively share resources. Since the Satlets are claimed to be capable of conforming to any size or shape on-orbit system, they could prove to be efficient payload upgrades to orbiting satellites. ISS assembly by astronauts done in October 2017.

Developer:	Novawurk	**Country:**	United States
First Use Date:	2017	**Status:**	Development

Performance Parameters:

Operation Type:	Modular Spacecraft
ORU SWaP:	Unavailable
Standard Interface Type:	Unavailable

6.4.7 PRUMI - 7: iBOSS iSSI

Description: The iBOSS (intelligent Building Blocks for On-Orbit Satellite Servicing and Assembly) project employs a new integrated approach on spacecraft modularity and standardization to allow for the possibility of OOS and the in-orbit replacement of common infrastructure elements. The modularity approach focuses on a 4-in-1 interface for mechanical coupling as well as power, data and thermal interconnection. The standard interface that came out of this project is the intelligent Space System Interface (iSSI).

Developer:	DLR Space Administration	**Country:**	Germany
First Use Date:	Unlisted	**Status:**	Development

Performance Parameters:

Operation Type:	Modular Interface
ORU SWaP:	Max Lateral load: 400Nm Power: 5kW Data Rate: 1 Gb/s Heat: 5W/K
Standard Interface Type:	Mechanical, Power, Data, Thermal

6.4.8 PRUMI - 8: Mag Tag

Description: EPM-based latching connector for enabling repair, fluid transfer, modular upgrades, and payload swapping

Developer:	Altius Space Machines	**Country:**	United States
First Use Date:	Unavailable	**Status:**	Development

Performance Parameters:

Operation Type:	Modular Interface
ORU SWaP:	Unavailable
Standard Interface Type:	Mechanical, others?

6.4.9 PRUMI - 9: Orbital Express

Description: Launched March 8, 2007 as part of the United States Air Force SpaceTest Program (STP), Orbital Express demonstrated automated rendezvous and capture of two spacecraft (ASTRO and NEXTSat), transfer of propellant, and transfer of a modular spacecraft component. Flow sensors demonstrated 5-10 percent flow rate error on N2H4 transfer with no significant issues. The mission demonstrated 9 mate/demate cycles on orbit and demonstrated robotic Orbital Replacement Unit (ORU) transfer and installation.

Developer:	DARPA, NASA	**Country:**	United States
First Use Date:	2007	**Status:**	Flown

Performance Parameters:

Operation Type:	Servicer
ORU SWaP:	Unavailable
Standard Interface Type:	Data, Power, Mechanical

6.4.10 PRUMI - 10: SOUL

Description: SOUL is a tethered robotic spacecraft that is designed to provide self-inspection and self-servicing. SOUL is a small (<10kg) robotic, self-propelled, self-navigating, autonomous vehicle that is equipped with a tool and that receives power & commands from the host spacecraft. It replaces a robotic arm and has the advantage of infinite degrees of freedom.

Developer:	Busek Co., Inc.	**Country:**	United States
First Use Date:	2018	**Status:**	Phase II testing

Performance Parameters:

Operation Type:	Repair servicer
ORU SWaP:	SOUL Unit stow in 6U container, mass of <10kg, peak power of <100W
Standard Interface Type:	N/A

6.4.11 PRUMI - 11: Standard Interface for Robotic Manipulation of Payloads in Future Space Missions (SIROM)

Description: SIROM is designed “to allow direct interaction with cooperative structures for service operations such as maintenance and construction work on technical infrastructure.” The project aims to standardize four interfaces: mechanical for mating and load transfer, data for data, TC & TM transfer, electrical for power transmission, and fluid for refueling. SENER, a commercial company involved in the development of SIROM, cites “payload upgrade or replacement for satellites” as an application of SIROM

Developer:	ESA (EU initiative)	**Country:**	Multiple, non-US
First Use Date:	2018 (testing)	**Status:**	Development

Performance Parameters:

Operation Type:	Modular Interface
ORU SWaP:	Max Lateral load: 40Nm Power: 150W Data: 100 Mbit/s Thermal: 2-2.5kW
Standard Interface Type:	Mechanical, Fluid (Thermal), Power, Data

6.4.12 PRUMI - 12: The Puck & Service Pods

Description: The Puck is a 4-in-1 interface combining mechanical, fluid, power, and data transfer capabilities is an alternative to other commonly used ground hardware interfaces. There is a passive puck to be equipped on the satellites receiving on-orbit services, and an active puck for the actual servicers. Orbuta’s website describes the service pods as follows: “Service Pods are Obruta's orbital service delivery systems. Each Service Pod incorporates rendezvous, proximity operations, and docking capabilities, and can host a variety of orbital service payloads to meet your spacecraft's needs.” One of the service pods’ key services is hardware replacement.

Developer:	Orbruta Space Solutions	**Country:**	Canada
First Use Date:	Unlisted	**Status:**	Development

Performance Parameters:

Operation Type:	Modular Interface
ORU SWaP:	Max Lateral load: 600 Nm Power: 4.8kW Data Rate: 10Gb/s Fluid rate: 4.0L/min @ 15 psi
Standard Interface Type:	Mechanical, Fluid, Power, Data

6.5 UNPLANNED OR LEGACY REPAIR AND MAINTENANCE

6.5.1 ULRM - 1: LEO Knight

Description: LEO Knight will provide the capability to assemble ESPA-class modules together to form persistent space platforms, capture space debris and transport it to recycling hubs, and refuel and repair small satellites.

Developer:	Tethers Unlimited	**Country:**	United States
First Use Date:	TBD	**Status:**	Development

Performance Parameters:

Repairable Subsystems / Components:	Refueling, deorbiting constellations, assembly of systems, delivery and integration of payloads
Repair Tools:	Kraken Robotic Arm
Grapple Types:	Kraken Robotic Arm

6.5.2 ULRM - 2: Mission Extension Pods

Description: Mission extension pods are Northrop's next generation of servicing vehicles. They will be smaller and less expensive life extension service that only performs orbit control, providing up to six years of life extension. They will be installed by a Mission Robotic Vehicle which can carry several pods.

Developer:	Northrup Grumman	**Country:**	United States
First Use Date:	2024 (Planned)	**Status:**	Development

Performance Parameters:

Repairable Subsystems / Components:	Unavailable
Repair Tools:	None in current design (planned for future)
Grapple Types:	Unavailable

6.5.3 ULRM - 3: Mission Robotic Vehicle (MRV)

Description: A future on-orbit servicing bus developed from the Mission Extension Vehicle. The robotic payload will be supplied by DARPA and developed by the US Naval Research Institute.

Developer:	Northrup Grumman	**Country:**	United States
First Use Date:	TBD	**Status:**	Development

Performance Parameters:

Repairable Subsystems / Components:	Unavailable
Repair Tools:	DARPA's two dexterous robotic manipulator arms, several tools and sensors
Grapple Types:	Unavailable

6.5.4 ULRM - 4: OSAM-1

Description: OSAM-1 is a robotic spacecraft equipped with the tools, technologies and techniques needed to extend satellites' lifespans - even if they were not designed to be serviced on orbit. During its mission, the OSAM-1 servicer will rendezvous with, grasp, refuel and relocate a government-owned satellite to extend its life. OSAM-1’s capabilities can give satellite operators new ways to manage their fleets more efficiently and derive more value from their initial investment. These capabilities could even help mitigate the looming problem of orbital debris. OSAM-1 will also be able to assemble a communications antenna and manufacture a beam on orbit.

Developer:	NASA/Maxar	**Country:**	United States
First Use Date:	TBD	**Status:**	Development

Performance Parameters:

Repairable Subsystems / Components:	Refueling, others unavailable
Repair Tools:	Dexterous Robotic Arms (2), Space Infrastructure Dexterous Robot (SPIDER), Autonomous Real-Time Relative Navigation System, Servicing Avionics, Advanced Tool Drive and Tools, Propellant Transfer
Grapple Types:	2 robotic arms, SPIDER arm

6.5.5 ULRM - 5: Robotic Refueling Mission (RRM)

Description: The Robotic Refueling Mission is a multi-phased International Space Station technology demonstration that is testing tools, technologies, and techniques to refuel and repair satellites in orbit - especially satellites not designed to be serviced. RRM gives NASA and the emerging commercial satellite servicing industry the confidence to robotically refuel, repair and maintain satellites in both near and distant orbits - well beyond the reach of where humans can go today. RRM is part of NASA’s Exploration and In-Space Services (NExIS) projects division, which is ushering in an era of more sustainable, affordable, and resilient spaceflight near Earth, the Moon and deep into the solar system.

Developer:	NASA	**Country:**	United States
First Use Date:	2012	**Status:**	Flown

Performance Parameters:

Repairable Subsystems / Components:	Repair Demo, Refueling Demo
Repair Tools:	Cameras and LEDs, Canadian Dextre Robot (Wire Cutter and Blanket Manipulation Tool, Multifunction Tool, Safety Cap Tool, Nozzle Tool), Robotic Fueling Hose, Visual Inspection Poseable Invertebrate Robot (VIPIR)
Grapple Types:	2 Dextre Arms

6.6 REFUELING AND FLUID TRANSFER

6.6.1 RFT - 1: Fluid Acquisition & Resupply Experiment I (FARE-I)

Description: Flown aboard STS-53 in 1992, the Fluid Acquisition & Resupply Experiment I (FARE-1) demonstrated an upgraded fluid management system over the SFMD, again with colored water. The screen-type system was tested 8 times and filled up to 70 percent without liquid venting.

Developer:	NASA MSFC	**Country:**	United States
First Use Date:	1992	**Status:**	Flown

Performance Parameters:

Propellant / Fluid Type:	Water
Fuel Volume / Mass:	Unavailable
Boil - Off Rate:	N/A

6.6.2 RFT - 2: Fluid Acquisition & Resupply Experiment II (FARE-II)

Description: Flown aboard STS-57 in 1993, the FARE-II demonstration followed SFMD and FARE-II and used a vane fluid management system. It demonstrated fill to 95 percent without liquid venting at a maximum flow rate of 0.35 gallons per minute. FARE-II again used colored water.

Developer:	NASA MSFC	**Country:**	United States
First Use Date:	1993	**Status:**	Flown

Performance Parameters:

Propellant / Fluid Type:	Water
Fuel Volume / Mass:	Unavailable
Boil - Off Rate:	N/A

6.6.3 RFT - 3: Furphy Prototype Tanker

Description: Orbit Fab's Furphy experiment transferred water between two tanks on ISS, then transferred that water to the ISS water supply. This demonstration advanced OrbitFab's propellant feed system to TRL 8.

Developer:	Orbit Fab	**Country:**	United States
First Use Date:	2019	**Status:**	Flown

Performance Parameters:

Propellant / Fluid Type:	Water
Fuel Volume / Mass:	Unavailable
Boil - Off Rate:	N/A

6.6.4 RFT - 4: NASA STMD 2020 Tipping Point Selections on Cryogenic Fluid Management Technology Demonstration

Description: Under the 2020 Tipping Point selections, NASA's Space Technology Mission Directorate (STMD) selected four industry partners to demonstrate numerous technologies to enable long-term cryogenic fluid management and transfer. Eta Space, Lockheed Martin, and United Launch Alliance (ULA) will demonstrate cryogenic oxygen (Eta Space) and hydrogen (Lockheed Martin) fluid management systems. Eta Space will develop a primary demonstration payload on a Rocket Lab Proton satellite for nine months. ULA will demonstrate management of both oxygen and hydrogen on a Vulcan Centaur upper stage, including precise tank pressure control, tank-to-tank transfer, and multi-week propellant storage. SpaceX will develop a large-scale flight demonstration to transfer 10 metric tons of cryogenic propellant, specifically liquid oxygen, between tanks on a Starship vehicle. These partners will collaborate with multiple NASA centers, including Marshall Space Flight Center, Glenn Research Center, and Kennedy Space Center.

Developer:	NASA, Eta Space, Lockheed Martin, SpaceX, United Launch Alliance
Country:	United States
First Use Date:	TBD
Status:	Development

Performance Parameters:

Propellant / Fluid Type:	LOX, LH2
Fuel Volume / Mass:	10 t (SpaceX demo), TBD for others
Boil - Off Rate:	Unavailable

6.6.5 RFT - 5: Orbital Express

Description: Launched March 8, 2007 as part of the United States Air Force SpaceTest Program (STP), Orbital Express demonstrated automated rendezvous and capture of two spacecraft (ASTRO and NEXTSat), transfer of propellant, and transfer of a modular spacecraft component. Flow sensors demonstrated 5-10 percent flow rate error on N2H4 transfer with no significant issues. The mission demonstrated 9 mate/demate cycles on orbit and demonstrated robotic Orbital Replacement Unit (ORU) transfer and installation.

Developer:	DARPA, NASA	**Country:**	United States
First Use Date:	2007	**Status:**	Flown

Performance Parameters:

Propellant / Fluid Type:	Hydrazine
Fuel Volume / Mass:	Unavailable
Boil - Off Rate:	N/A

6.6.6 RFT - 6: Orbital Refueling System (ORS) Flight Demonstration

Description: Flown aboard STS-41G in 1984, the Orbital Refueling System (ORS) demonstrated the feasibility of refueling hydrazine. Housed in the Shuttle Payload Bay, an EVA connected two tanks (one simulating a tanker and another simulating a satellite to be refueled). The experiment involved transferring up to 142 kg of propellant 6 times between the tanks. Nitrogen was used as pressurant to inflate a bladder.

Developer:	NASA JSC	**Country:**	United States
First Use Date:	1984	**Status:**	Flown

Performance Parameters:

Propellant / Fluid Type:	Hydrazine
Fuel Volume / Mass:	142 kg
Boil - Off Rate:	N/A

6.6.7 RFT - 7: OSAM-1

Description: Planned to launch in 2024, the OSAM-1 servicer will rendezvous with, grasp, refuel, and relocate the Landsat 7 spacecraft in LEO to extend its life. During the refueling mission, OSAM-1 will cut away MLI, remove the propellant fill valves, and attach a cooperative servicing valve to enable transfer of hydrazine.

Developer:	NASA	**Country:**	United States
First Use Date:	2024	**Status:**	Development

Performance Parameters:

Propellant / Fluid Type:	Hydrazine
Fuel Volume / Mass:	Unavailable
Boil - Off Rate:	N/A

6.6.8 RFT - 8: Progress Vehicle and ATV Refueling of ISS

Description: The Russian Progress vehicle is used to deliver cargo and fluids to the ISS. The Progress can transfer fuel (UDMH), oxidizer (NTO), and water. The vehicle can hold up to 1740 kg depending on amount of cargo the Progress also carries to the ISS. The fluids can be transferred to ISS using the docking ring. This propellant can also be used by the Progress's thrusters to maneuver ISS. This spacecraft and propellant transfer system were first used on Salyut 6 in 1978, was used on the Mir space station, and has been used on ISS since 2000. ESA's Automated Transfer Vehicle (ATV) has also refueled ISS since 2011.

Developer:	Roscosmos, ESA	**Country:**	Russia, Europe
First Use Date:	2000	**Status:**	Flown

Performance Parameters:

Propellant / Fluid Type:	NTO, UDMH, Water
Fuel Volume / Mass:	up to 1740 kg
Boil - Off Rate:	N/A

6.6.9 RFT - 9: Robotic Refueling Mission 3 (RRM3)

Description: The Robotic Refueling Mission 3 (RRM3) stored liquid methane for 4 months on ISS in 2018. Cryogenic mass gauging and zero boiloff was demonstrated. Cryocooler failure prevented the cryogenic propellant transfer demonstration that was planned. Gauging uncertainty was 2 percent.

Developer:	NASA GSFC	**Country:**	United States
First Use Date:	2018	**Status:**	Flown

Performance Parameters:

Propellant / Fluid Type:	Methane
Fuel Volume / Mass:	Unavailable
Boil - Off Rate:	~ zero

6.6.10 RFT - 10: Storage Fluid Management Demonstration (SFMD)

Description: Flown aboard STS-51C in 1985, the Storage Fluid Management Demonstration (SFMD) tested a fluid acquisition device using colored water and air. In transferring water into the demonstration tank, a maximum of 85% fill was achieved at a maximum flow rate of 1 gallon per minute, but the system of baffles and screened liquid acquisition device was unsuccessful at orienting liquid away from the tank's vent port. Nine tests were performed.

Developer:	Martin Marietta	**Country:**	United States
First Use Date:	1985	**Status:**	Flown

Performance Parameters:

Propellant / Fluid Type:	Water
Fuel Volume / Mass:	Unavailable
Boil - Off Rate:	N/A

6.6.11 RFT - 11: Superfluid Helium On-Orbit Transfer (SHOOT) Flight Demonstration

Description: Superfluid helium was transferred between tanks on the Superfluid Helium On-Orbit Transfer (SHOOT) flight demonstration on STS-57 in 1993. The experiment used the unique property of superfluid helium to move the fluid between two tanks. Some fluid boiled off with each transfer, and the unique properties of superfluid helium make the demonstration difficult to translate to other fluids.

Developer:	NASA	**Country:**	United States
First Use Date:	1993	**Status:**	Flown

Performance Parameters:

Propellant / Fluid Type:	Helium
Fuel Volume / Mass:	152 L
Boil - Off Rate:	> 0

6.6.12 RFT - 12: Tanker-001 Tenzing

Description: OrbitFab launched its first propellant depot in June 2021, storing the green propellant High-Test Peroxide in a sun-synchronous orbit. The Tenzing contains the Rapidly Attachable Fluid Transfer Interface (RAFTI) service valve for fill/drain on orbit and alignment markers to assist with rendezvous and proximity operations. The Space Coupling Half (other side of Service Valve for client spacecraft) supports the docking of the two spacecraft.

Developer:	OrbitFab	**Country:**	United States
First Use Date:	2021	**Status:**	Flown

Performance Parameters:

Propellant / Fluid Type:	High-Test Peroxide (HTP)
Fuel Volume / Mass:	Unavailable
Boil - Off Rate:	N/A

6.6.13 RFT - 13: Tianyuan 1 refueling demonstration

Description: Launched in 2016, the Tianyuan 1 spacecraft demonstrated satellite refueling in orbit.

Developer:	National University of Defense Technology
Country:	China
First Use Date:	2016
Status:	Flown

Performance Parameters:

Propellant / Fluid Type:	Unavailable
Fuel Volume / Mass:	Unavailable
Boil - Off Rate:	Unavailable

6.7 STRUCTURAL MANUFACTURING AND ASSEMBLY

6.7.1 SMA - 1: Archinaut

Description: The technology demonstration, previously called Archinaut One and now OSAM-2, will manufacture and deploy its own operational solar array.

Developer:	Made in Space, MSFC	**Country:**	USA
First Use Date:	Unavailable	**Status:**	Development

Performance Parameters:

Max. Dimensions:	10m for ESPA class satellites
Material Type(s):	PEI/PC
Joining:	3D printed
Assembly Agent:	Robot
Operation Regime:	On-Orbit, In-Space
Technology Area:	Robotic Assembly, manufacturing

6.7.2 SMA - 2: Motiv Robotic Arm

Description: The Motiv robot arm will be used aboard the OSAM-2 mission to assist in the manufacturing and reconfiguration needed during the technology demonstration mission.

Developer:	NASA, Made in Space, Northrop Grumman, JPL	**Country:**	USA
First Use Date:	Unavailable	**Status:**	Development

Performance Parameters:

Max. Dimensions:	"scalable"
Material Type(s):	Metal Structure
Joining:	N/A (gripper only)
Assembly Agent:	Robot
Operation Regime:	On-Orbit
Technology Area:	Robotic Arm

6.7.3 SMA - 3: Assemblers

Description: Collective project goal of increasing the TRL for modular robots, autonomous in-space assembly, and to develop a robotic prototype for ground testing. To reach the goal of the project both new hardware and software is being developed.

Developer:	NASA LaRC	**Country:**	USA
First Use Date:	Unavailable	**Status:**	Development

Performance Parameters:

Max. Dimensions:	"scalable"
Material Type(s):	Metal Structure
Joining:	N/A (end-effector)
Assembly Agent:	Robot
Operation Regime:	On-Orbit, In-Space, Terrestrial
Technology Area:	Robotic Assembly

6.7.4 SMA - 4: Beam Fabricator

Description: As part of the OSAM-2 mission, the Beam Fabricator will demonstration the manufacturing of a beam in space.

Developer:	Tethers Unlimited	**Country:**	USA
First Use Date:	Unavailable	**Status:**	Development

Performance Parameters:

Max. Dimensions:	10m Truss Fabricated
Material Type(s):	Carbon Fiber
Joining:	"Extrusion with Post Assembly"
Assembly Agent:	Robot
Operation Regime:	On-Orbit, In-Space
Technology Area:	Robotic Assembly, manufacturing

6.7.5 SMA - 5: EASE/Access

Description: Space shuttle flight experiments that studied astronaut efficiency, fatigue, and construction and maintenance techniques for construction of space structures.

Developer: NASA **Country:** USA
First Use Date: 1985 **Status:** Complete

Performance Parameters:
Max. Dimensions: Unavailable
Material Type(s): Metal Structure
Joining: Nodal Joints
Assembly Agent: Human
Operation Regime: On-Orbit, ISS
Technology Area: Human Assembly

6.7.6 SMA - 6: Hinge for Use in a Tension Stiffened and Tendon Actuated Manipulator

Description: The hinge connecting adjacent link arms together to allow the adjacent link arms to rotate relative to each other and a cable actuation and tensioning system provided between adjacent link arms; When in a stowed position, the centerlines of the first and second link arms and the central member are parallel to each other. Axis is offset from, but parallel to, the centerline of the central member.

Developer: NASA **Country:** USA
First Use Date: N/A **Status:** Development

Performance Parameters:
Max. Dimensions: Approx. 360˚ rotation
Material Type(s): Metal Structure
Joining: N/A
Assembly Agent: N/A
Operation Regime: On-Orbit, In-Space
Technology Area: Robotic Arm Joint

6.7.7 SMA - 7: Joint Design Using Electron Beam Welding for Autonomous In-Space Truss Assembly (EBW Joint)

Description: A Metallic 3D printable Joint system design for easy robotic handling, and welding with room for adjustment. Although initially, the joint is designed to be used with electronic beam welding, it can be configured to be used with other welding process such as LASER or traditional welding.

Developer:	NASA	**Country:**	USA
First Use Date:	N/A	**Status:**	Development

Performance Parameters:

Max. Dimensions:	N/A
Material Type(s):	N/A
Joining:	E-Beam Welding
Assembly Agent:	Robot/Human
Operation Regime:	On-Orbit, In-Space
Technology Area:	Structure Joint

6.7.8 SMA - 8: NASA Intelligent Jigging and Assembly Robot (NINJAR)

Description: A Stewart Platform with 6 to 14 degrees of freedom; may be configured to uses a smart jig for building trusses or similar structural system with alignment error correction capability. Can also be attached to a long reach manipulator to enhance precision and dexterity to aide fine precision operation.

Developer:	NASA	**Country:**	USA
First Use Date:	N/A	**Status:**	Development

Performance Parameters:

Max. Dimensions:	30 x 30 x 30 cube
Material Type(s):	Metal Structure
Joining:	N/A
Assembly Agent:	Robot
Operation Regime:	On-Orbit, In-Space, Terrestrial
Technology Area:	Robotic Assembly

6.7.9 SMA - 9: Precision Assembled Space Structures (PASS)

Description: Modular assembly architecture to assemble a tri-truss system for applications such as reflectors. This design will be scalable and will use a path to flight approach.

Developer:	NASA	**Country:**	USA
First Use Date:	N/A	**Status:**	Development

Performance Parameters:

Max. Dimensions: "scalable"
Material Type(s): N/A
Joining: N/A
Assembly Agent: Robot
Operation Regime: On-Orbit, In-Space
Technology Area: Robotic Assembly

6.7.10 SMA - 10: Robotically Compatible Erectable Joint with Square Cross-Section

Description: Erectable joint design with a square cross-section at the interface to support robotic assembly that is functionally derived from the mechanical pre-load physics of LaRC's existing round erectable joint.

Developer:	NASA	**Country:**	USA
First Use Date:	N/A	**Status:**	Development

Performance Parameters:

Max. Dimensions: N/A
Material Type(s): Metal Structure
Joining: N/A
Assembly Agent: N/A
Operation Regime: On-Orbit, In-Space, Terrestrial
Technology Area: Robotic Arm Joint

6.7.11 SMA - 11: SHEAth-based Rollable Lenticular-Shaped and Low-Stiction (SHEARLESS) Composite Booms

Description: Rollable and deployable composite booms that may be used in a wide range of applications both for space and terrestrial structural solutions. Composite booms may be bistable, i.e., having a stable strain energy minimum in the coiled configuration as well as the in the deployed configuration.

Developer:	NASA	**Country:**	USA
First Use Date:	N/A	**Status:**	Development

Performance Parameters:

Max. Dimensions:	Unavailable
Material Type(s):	Composite
Joining:	N/A
Assembly Agent:	N/A
Operation Regime:	On-Orbit, In-Space
Technology Area:	Deployable

6.7.12 SMA - 12: Space Infrastructure Dexterous Robot (SPIDER)

Description: The OSAM-1 spacecraft will include an attached payload called Space Infrastructure Dexterous Robot (SPIDER). SPIDER includes a lightweight 16-foot (5-meter) robotic arm, bringing the total number of robotic arms flying on OSAM-1 to three. Previously known as Dragonfly during the ground demonstration phase of the NASA Tipping Point partnership, SPIDER will assemble seven elements to form a functional 9-foot (3-meter) communications antenna.

Developer:	Maxar	**Country:**	USA
First Use Date:	N/A	**Status:**	Development

Performance Parameters:

Max. Dimensions:	5 m
Material Type(s):	Metal Structure
Joining:	N/A (end-effector)
Assembly Agent:	Robot
Operation Regime:	On-Orbit
Technology Area:	Robotic Arm

6.7.13 SMA - 13: Structural Joint with Multi-Axis Load Carrying Capability

Description: A composite joint connector that is more structurally efficient than joints currently on the market. Traditionally, composite joints can bear heavy loads along their length but tend to fail when stress is applied along multiple axes. This joint is designed to minimize stress concentrations, leading to overall increased structural efficiency when compared to traditional joints.

Developer:	NASA	**Country:**	USA
First Use Date:	1992	**Status:**	Flown

Performance Parameters:

Max. Dimensions:	2-inch
Material Type(s):	Composite
Joining:	Bonded
Assembly Agent:	N/A
Operation Regime:	N/A
Technology Area:	Structure Joint

6.7.14 SMA - 14: Strut Attachment, Manipulation, and Utility Robotic Aide (SAMURAI)

Description: A scalable modular strut/component attachment handling system; may be configured into various forms to handle a variety of system components, such as structure elements, structure module, or other modules that need to be assembled. Its function includes but not limited to component retrieve and attachment.

Developer:	NASA	**Country:**	USA
First Use Date:	N/A	**Status:**	Development

Performance Parameters:

Max. Dimensions:	46 in.
Material Type(s):	Metal Structure
Joining:	N/A
Assembly Agent:	Robot
Operation Regime:	On-Orbit, In-Space, Terrestrial
Technology Area:	Robotic Assembly

6.8 RECYCLING, REUSE, AND REPURPOSING

6.8.1 RRR - 1: Metal Advanced Manufacturing Bot-Assisted Assembly (MAMBA)

Description: The Metal Advanced Manufacturing Bot-Assisted Assembly (MAMBA) ground demonstration prototype was developed to process virgin or metal scrap material into ingots that could then be machined or milled to a final part. Debris from machining of metal to fabricate a part is collected and can be used for further ingot manufacturing.

Developer:	Tethers Unlimited, NASA
Country:	USA
First Use Date:	2017
Status:	Ground Development, Complete/Ended

Performance Parameters:

Recyclable Materials / Items:	Metal
Product:	Metal ingots

6.8.2 RRR - 2: Recyclable Packaging Materials

Description: NASA's In-Space Manufacturing program is advancing (with commercial partners) multiple technologies in recyclable packaging materials and sustainable approaches to enable a recycling ecosystem in space, such as:

- Polyethylene based thermally reversible material can be processed into films and foams and recycled into filament for 3D printing (Cornerstone Research Group)
- Customizable, Recyclable ISS Packaging (CRISSP) - Polymer 3D printed foams with custom infills engineered for specific vibration attenuation properties (Tethers Unlimited, Inc.)
- ERASMUS is a multimaterial recycling capability with an integrated dry heat sterilization chamber for polymer parts (Tethers Unlimited, Inc.)
- Automated in-process quality control of recycled filament production and polymer 3D printing (Cornerstone Research Group)

Developer:	Cornerstone Research Group, Tethers Unlimited, NASA	**Country:**	USA
First Use Date:	2019	**Status:**	Development

Performance Parameters:

Recyclable Materials / Items:	Multimaterial Polymers
Product:	Multiple products, incl. filament feedstock and packaging materials

6.8.3 RRR - 3: ReFabricator

Description: Installed on International Space Station in early 2019, the ReFabricator has the capability to recycle printed polymer parts into filament feedstock for further manufacturing. ReFabricator is an integrated 3D printer and recycler for ULTEM 9085, a thermoplastic. Upon initial startup, an anomaly in the recycling system occurred.

Developer:	Tethers Unlimited, NASA	**Country:**	USA
First Use Date:	2019	**Status:**	Flown

Performance Parameters:

Recyclable Materials / Items:	Thermoplastic polymers
Product:	Filament feedstock for 3D printing

6.8.4 RRR - 4: Tailored Universal Feedstock for Forming (TuFF) Reformability Demo

Description: Small contract funded a small demo of how short fibers developed by the University of Delaware under a DARPA grant to develop fibers for composites that are lower cost (i.e. level of cost for automotives) with aerospace grade performance can support repurposability. TuFF proven to yield composites with performance equivalent to IM7/8552. The contract was a small demo to determine what would be required to reform the composite part. They demonstrated approaches to get 45° & 90° bends.

Developer:	University of Delaware/ Composites Automation LLC	**Country:**	USA
First Use Date:	2020	**Status:**	Development

Performance Parameters:

Recyclable Materials / Items:	Thermoplastic composites with short carbon fibers
Product:	Coupons

6.8.5 RRR - 5: Thermally Reversible Polymers for AM Feedstock

Description: First funded as a Phase 1 SBIR in 2016, the Thermally Reversible Polymers for AM Feedstock project was also funded for Phase 2. The project was able to demonstrate that a component can be made with a resin and then reprocessed with properties needed for structural composites. Multiple parts were created with a reformable resin and then reshaped into other parts representing potential structural parts for planetary use.

Developer:	Cornerstone Research Group	**Country:**	USA
First Use Date:	2016	**Status:**	Development

Performance Parameters:

Recyclable Materials / Items:	Thermally reversible polymers
Product:	Panels, tubes, and other geometries made with recycled composite

6.9 PARTS AND GOODS MANUFACTURING

6.9.1 PGM - 1: 3D Printing in Zero G TDM

Description: Printed 55 parts of Acryonitrile Butadiene Styrene (ABS) from 2014-2016. Printer operates in Microgravity Science Glovebox (MSG).

Developer:	Made in Space, NASA	**Country:**	USA
First Use Date:	2014	**Status:**	Flown

Performance Parameters:

End Product:	Finished Part
Inputs:	Earth Delivered Material
Max. Dimensions:	6 cm x 12 cm x 6 cm
Material Type:	ABS
Operation Regime:	On-Orbit (ISS)
Operator:	Human / Remote Human

6.9.2 PGM - 2: Additive Manufacturing Facility (AMF)

Description: Multimaterial commercial facility for polymer printing from Made in Space, Inc. Printed over 100 mechanical test coupons (flight and ground-produced specimens).

Developer:	Made in Space, NASA	**Country:**	USA
First Use Date:	2016	**Status:**	Flown

Performance Parameters:

End Product:	Finished Part
Inputs:	Earth Delivered Material
Max. Dimensions:	14 cm x 10 cm x 10 cm
Material Type:	ABS, HDPE, PEI-PC initially, more upon ISS approval
Operation Regime:	On-Orbit (ISS)
Operator:	Human

6.9.3 PGM - 3: Multimaterial Fabrication Laboratory

Description: Parallel efforts under a Broad Agency Announcement (BAA) to develop larger scale facilities for multi-material manufacturing (focus on aerospace metals) and inspection. 18-month phase A efforts, focused on development of ground-based prototype systems and technology demonstration. Multimaterial Fabrication Laboratory was the BAA opportunity to develop a multimaterial printer (with a focus on metals and in-process inspection capabilities) for ISS. There were 3 companies who were funded (Interlog, Tethers Unlimited, and Techshot). Techshot was the only one who continued froward and that is now known as Techshot FabLab. Techshot FabLab is a bound metal additive manufacturing system that includes a furnace for part sintering and a laser line profilometer for in-process monitoring of the print).

Developer:	Techshot, Interlog, Tethers Unlimited, NASA	**Country:**	USA
First Use Date:	TBD	**Status:**	Development

Performance Parameters:

End Product:	Finished Part
Inputs:	Earth Delivered Material
Max. Dimensions:	6 in. x 6 in. x 6 in.
Material Type:	Metallics and Polymers
Operation Regime:	On-Orbit (ISS)
Operator:	Human, Remote Human, autonomous

6.9.4 PGM - 4: On-Demand Manufacturing of Electronics (ODME)

Description: ODME is developing printed electronics, sensors, and power devices for demonstration on ISS. In parallel, deposition processes used with printed electronics (direct write and plasma jet) are being matured for future flight demos. Astrosense leverages printed electronics, creating a wireless wearable sensor device for astronaut crew health monitoring. The integrated sensor capability is slated for ISS demonstration by 2024.

Developer:	NASA	**Country:**	USA
First Use Date:	2024	**Status:**	Development

Performance Parameters:

End Product:	Finished Assembly
Inputs:	N/A
Max. Dimensions:	N/A
Material Type:	Polymers and Electronics
Operation Regime:	On-Orbit (ISS)
Operator:	Human

6.9.5 PGM - 5: Redwire Regolith Print (RegISS)

Description: RegISS will be an on-orbit demonstration of 3D printing with a polymer/regolith simulant feedstock blend. It will be the first demonstration of manufacturing with ISRU-derived feedstocks on ISS. This proof of concept will show the viability of printing with regolith composite material in a reduced gravity environment and is applicable to manufacturing on the lunar surface and Mars. In this effort, a previously flown version of AMF will be modified to accommodate a new extruder and print with a feedstock consisting of regolith simulant and a thermoplastic.

Developer:	Made In Space, Redwire, NASA	**Country:**	USA
First Use Date:	TBD	**Status:**	Development

Performance Parameters:

End Product:	Finished Part
Inputs:	ISRU
Max. Dimensions:	TBD (likely the size of the AMF)
Material Type:	Regolith simulant feedstock blend
Operation Regime:	On-Orbit (ISS)
Operator:	Human

6.9.6 PGM - 6: Sintered Inductive Metal Printer with Laser Exposure (SIMPLE)

Description: Wire-fed additive manufacturing process for metals. Uses inductive heating and operates in a vacuum. Low power laser provides additional heating.

Developer:	Techshot, Inc., NASA	**Country:**	USA
First Use Date:	TBD	**Status:**	Complete/Ended

Performance Parameters:

End Product:	Finished Part
Inputs:	Earth Delivered Material
Max. Dimensions:	Unavailable
Material Type:	Metallic
Operation Regime:	Microgravity (any NASA Vehicle)
Operator:	Human

6.9.7 PGM - 7: Vulcan

Description: Derived from wire-fed welding process. Wire-fed metal 3D printer from Made in Space (Wire+arc additive with CNC machining). Started as an SBIR (phase I, II, and II-E), but has since transitioned to a contract with ISS Research Office.

Developer:	Made in Space, NASA	**Country:**	USA
First Use Date:	2024	**Status:**	Development

Performance Parameters:

End Product:	Finished Part
Inputs:	Earth Delivered Material
Max. Dimensions:	Unavailable
Material Type:	Metallics and Polymers
Operation Regime:	On-Orbit (ISS)
Operator:	Human

6.10 SURFACE CONSTRUCTION

6.10.1 SC - 1: 3D Printed Habitat Challenge

Description: In an effort to crowdsource ideas, NASA developed the 3D Printed Habitat Challenge. This Challenge took place in three phases. The Phase I competition awarded prize money for an optimal design of a 3D printed habitat. The Phase 2 competition focused on the composition and strength of 3D printed material of a Martian regolith and recycled trash composition. Phase 3 included three levels for 3D printing of subscale habitats with perforations and structural requirements as well as two levels for virtual Building Information Modeling competitions for a fully outfitted virtual habitat.

Developer:	NASA	**Country:**	USA
First Use Date:	N/A	**Status:**	Development

Performance Parameters:

Materials (Imported v. ISRU):	ISRU
Construction Agent:	Robot
Auto / Fly-by-Wire / Planned:	Planned

6.10.2 SC - 2: Additive Construction with Mobile Emplacement (ACME)

Description: In 2014, a joint venture between NASA's Space Technology Mission Directorate Game Changing Development Program and the United States Army Corps of Engineers (USACE) resulted in the Additive Construction with Mobile Emplacement (ACME) project. ACME combined the expertise, technology, and goals of NASA's MSFC and John F. Kennedy Space Center (KSC), the USACE, Contour Crafting Corporation (CCC, headed by B. Khoshnevis), and the Pacific International Space Center for Exploration Systems. By 2018, the project successfully completed additive construction (both 2D landing pad and 3D wall construction) demonstrations with materials made from simulated planetary regolith.

Additional work related to ACME includes two Center Innovation Fund efforts awarded by the MSFC Chief Technologist, as well as the Additive Construction of Expeditionary Structures (ACES) project under the USACE.

Developer:	NASA, US Army Corps of Engineers	**Country:**	USA
First Use Date:	N/A	**Status:**	Development

Performance Parameters:

Materials (Imported v. ISRU):	ISRU
Construction Agent:	Human
Auto / Fly-by-Wire / Planned:	Planned

6.10.3 SC - 3: ARMADAS

Description: The Automated Reconfigurable Mission Adaptive Digital Assembly Systems (ARMADAS) project will develop and demonstrate autonomous assembly of building block-based “digital materials” and structures. This will present automation technologies with potential for meeting along duration and deep space infrastructure needs, including achieving in-space reliance with construction and maintenance of long duration spaceport and habitat scale systems.

Developer:	NASA ARC	**Country:**	USA
First Use Date:	N/A	**Status:**	Development

Performance Parameters:

Materials (Imported v. ISRU):	ISRU
Construction Agent:	Robot
Auto / Fly-by-Wire / Planned:	Auto

6.10.4 SC - 4: CHAPEA

Description: The Crew Health and Performance Analog (CHAPEA) project has two main purposes: to run an analog to understand crew health and performance outcomes associated with their operational trades, as well as to demonstrate design and construction of a regolith 3D printed habitat for Mars. The CHAPEA team partnered with ICON to 3D print a realistic Mars habitat using lavacrete, with the intention to maximize in situ resource utilization. Led by JSC's Michele Parker.

Developer:	NASA JSC	**Country:**	USA
First Use Date:	N/A	**Status:**	Habitat construction in progress as of July 2021

Performance Parameters:

Materials (Imported v. ISRU):	ISRU and possibly imported binder
Construction Agent:	Robot
Auto / Fly-by-Wire / Planned:	Planned

6.10.5 SC - 5: GaLORE Project

Description: The Gaseous Lunar Oxygen from Regolith Electrolysis (GaLORE) project team won an internal award to develop the melting technology. Regolith on the Moon is made from oxidized metals like iron oxide, silicon oxide and aluminum oxide. GaLORE is advancing technology to heat the regolith to more than 3,000 degrees Fahrenheit and flow electricity through the molten material. This will cause a chemical reaction that splits the regolith into gaseous oxygen and metals.

Developer:	NASA KSC	**Country:**	USA
First Use Date:	N/A	**Status:**	Development

Performance Parameters:

Materials (Imported v. ISRU):	ISRU
Construction Agent:	Robot
Auto / Fly-by-Wire / Planned:	Auto

6.10.6 SC - 6: In Situ Construction GCD Project

Description: FY21 Selected program by Game Changing Development Program that delayed its funding until FY22. Project is being rescoped and reformulated based on the lessons learned during the MMPACT, Lunar Safe Haven Study, and other work in FY21. Focus on Landing Pads. Led by KSC's Nathan Gelino. Moses is matrixed from LaRC.

Developer:	NASA KSC	**Country:**	USA
First Use Date:	N/A	**Status:**	Development

Performance Parameters:

Materials (Imported v. ISRU):	ISRU and options for imported binders
Construction Agent:	Unavailable
Auto / Fly-by-Wire / Planned:	Unavailable

6.10.7 SC - 7: In-Situ Fabrication and Repair Project (ISFR)

Description: In the 2004-2007 timeframe, habitats and structures were part of the In-Situ Fabrication and Repair (ISFR) project at NASA's George C. Marshall Space Flight Center (MSFC). The ISFR program developed technologies for fabrication, repair and recycling of tools, parts, and habitats and other structures using in-situ resources. The in-situ resources evaluated during this time included lunar raw materials, recycled spacecraft, human waste, trash, etc. Approximately 27 different research projects were funded by this effort, including identification and usage of raw materials (e.g., regolith, rocks, and lava tubes), autonomous construction technologies such as an inflatable dome (D. Bini, inventor) and contour crafting (B. Khoshnevis, inventor). Processing technologies funded by the ISFR effort included glass melting for structural members and rebar, as well as foldable and deployable structures.

Developer:	NASA MSFC	**Country:**	USA
First Use Date:	N/A	**Status:**	Development

Performance Parameters:

Materials (Imported v. ISRU):	ISRU
Construction Agent:	Human
Auto / Fly-by-Wire / Planned:	Fly by Wire

6.10.8 SC - 8: LANCE

Description: The Lunar Attachment Node for Construction and Excavation (LANCE) is a lightweight bulldozer blade designed to attach to the Chariot chassis. LANCE was developed at KSC and tested in lunar regolith simulant in 2008. Led by Robert Mueller.

Developer:	NASA KSC	**Country:**	USA
First Use Date:	N/A	**Status:**	Complete

Performance Parameters:

Materials (Imported v. ISRU):	Imported
Construction Agent:	Robot
Auto / Fly-by-Wire / Planned:	Planned

6.10.9 SC - 9: Lightweight Surface Manipulator System (LSMS)

Description: Lightweight Surface Manipulation System (LSMS) is a crane with multiple end effectors being developed at NASA Langley. LSMS is designed to be scalable to a wide range of reach and tip mass requirements, with 12 years of design heritage and testing on 1000 kg (lunar) tip mass capable prototype unit. The LSMS is currently funded (2021 to 2023) by STMD Game Changing Developments (GCD). Led by Thomas C. Jones.

Developer:	NASA LaRC	**Country:**	USA
First Use Date:	N/A	**Status:**	Development

Performance Parameters:

Materials (Imported v. ISRU):	Imported
Construction Agent:	Robot
Auto / Fly-by-Wire / Planned:	Planned

6.10.10 SC - 10: MMPACT

Description: The MMPACT project will focus on the utilization of lunar in-situ materials for the manufacturing construction of large-scale infrastructure elements like habitats, berms, landing pads, blast shields, walkways, floors, storage facilities, and roads using one or both of two techniques.

Developer:	NASA MSFC, ICON	**Country:**	USA
First Use Date:	N/A	**Status:**	Development

Performance Parameters:

Materials (Imported v. ISRU):	ISRU
Construction Agent:	Human
Auto / Fly-by-Wire / Planned:	Planned

6.10.11 SC - 11: RASSOR

Description: RASSOR is a teleoperated mobile robotic platform with a unique space regolith excavation capability. Its design incorporates net-zero reaction force, thus allowing it to load, haul, and dump space regolith under extremely low gravity conditions with high reliability. Two designs, one for ISRU and one for regolith excavation.

Developer:	NASA KSC	**Country:**	USA
First Use Date:	N/A	**Status:**	Development

Performance Parameters:

Materials (Imported v. ISRU):	ISRU and Construction
Construction Agent:	Robot
Auto / Fly-by-Wire / Planned:	Planned

6.10.12 SC - 12: REACT

Description: Relevant Environment Additive Construction Technology (REACT) is funded by a NASA ACO (Announcement of Collaborative Opportunity) contract between AI SpaceFactory and KSC in 2021 until (Unknown end date). Additionally, AI SpaceFactory contracted LERA, a structural engineering consulting firm. The REACT team is designing a safe haven type structure and developing the associated construction technologies and materials necessary for a large, regolith polymer composite based 3D printed structure on the lunar surface. By the end of the project, the REACT team intends to demonstrate the material and structural design. KSC team led by Nathan Gelino.

Developer:	AI SpaceFactory, LERA, NASA KSC	**Country:**	USA
First Use Date:	N/A	**Status:**	Development

Performance Parameters:

Materials (Imported v. ISRU):	ISRU and possibly imported binder
Construction Agent:	Robot
Auto / Fly-by-Wire / Planned:	Planned

6.10.13 SC - 13: Redwire Regolith Print (RegISS)

Description: RegISS will be an on-orbit demonstration of 3D printing with a polymer/regolith simulant feedstock blend. It will be the first demonstration of manufacturing with ISRU-derived feedstocks on ISS. This proof of concept will show the viability of printing with regolith composite material in a reduced gravity environment and is applicable to manufacturing on the lunar surface and Mars. In this effort, a previously flown version of AMF will be modified to accommodate a new extruder and print with a feedstock consisting of regolith simulant and a thermoplastic.

Developer:	Made in Space, NASA	**Country:**	USA
First Use Date:	N/A	**Status:**	Development

Performance Parameters:

Materials (Imported v. ISRU):	ISRU
Construction Agent:	Robot
Auto / Fly-by-Wire / Planned:	Planned

6.11 INSPECTION AND METROLOGY

6.11.1 IM - 1: AeroCube-10 (AC-10)

Description: Pair of 1.5U CubeSats (one with 28 deployable atmospheric probes and laser beacon, another with camera and propulsion system). AC-10B entered "orbit" around AC-10A and used on-board camera to take resolved images of AC-10A. AC-10B took photos from 22 meters away.

Developer:	The Aerospace Corporation	**Country:**	USA
First Use Date:	2019	**Status:**	Flown

Performance Parameters:

Contact:	N, Free-flying
Inspection Type:	Visual
Resolution:	<10 meters
Inspection Aides / Fiducials / Cues:	GPS, ADCS, Ground Station comms
Data Analysis:	Off-board

6.11.2 IM - 2: Alpha Magnetic Spectrometer (AMS-02)

Description: The AMS-02 is a particle physics detector designed to operate as an external module on the ISS. It uses the unique environment of space to study the universe and its origin by searching for antimatter, dark matter while performing precision measurements of cosmic rays composition and flux.

Developer:	US Dept of Energy, NASA	**Country:**	USA
First Use Date:	2011	**Status:**	Flown

Performance Parameters:

Contact:	Y, Truss mounted
Inspection Type:	High-Energy Particles (eV)
Resolution:	1%, up to TeV region
Inspection Aides / Fiducials / Cues:	Transition Radiation Detector, Permanent magnets, Time of Flight counters, Ring Image Cherenkov Counter, Electromagnetic Calorimeter
Data Analysis:	Off-board

6.11.3 IM - 3: ANGELS

Description: Automated Navigation and Guidance Experiment for Local Space evaluates SSA techniques in region around its Delta-4 launch vehicle upper stage. Beginning experiments approximately 50 km away from the upper stage and progressing to within several kilometers. Uses ground commanded authorization to proceed points throughout the experiment.

Developer:	AFRL	**Country:**	USA
First Use Date:	2014	**Status:**	Flown

Performance Parameters:

Contact:	N, free-flying
Inspection Type:	Visual
Resolution:	High
Inspection Aides / Fiducials / Cues:	SSA Sensor payload, GPS, accelerometers
Data Analysis:	Autonomous

6.11.4 IM - 4: Bio-memetic Snake Arm Robot

Description: The Bio-memetic snake arm robot was considered to help repair parts of the ISS that are behind racks or assemblies not easily accessible to astronauts. It would come equipped with a camera and grabbing tool at the end and its "body" would be able to sense objects around it so as to maneuver around them.

Developer:	NASA	**Country:**	USA
First Use Date:	TBD	**Status:**	Concept

Performance Parameters:

Contact:	Y, Robot-arm
Inspection Type:	Visual
Resolution:	High
Inspection Aides / Fiducials / Cues:	Stereo vision, articulating head, swappable head sensor
Data Analysis:	Off-board

6.11.5 IM - 5: Laura

Description: Inspection and monitoring with high-definition cameras and sensors. Multispectral capabilities to extend customer insight and analysis without having to come in contact with the target asset.

Developer:	Rogue Space Systems Corporation	**Country:**	USA
First Use Date:	2022	**Status:**	Development

Performance Parameters:

Contact:	N, free-flying
Inspection Type:	Visual
Resolution:	High
Inspection Aides / Fiducials / Cues:	Multispectral sensor capabilities
Data Analysis:	Off-board

6.11.6 IM - 6: Mycroft

Description: 4th generational experimental SSA spacecraft that builds upon technology, knowledge, and lessons learned from XSS-10, XSS-11, and ANGELS. Evaluates region around EAGLE using SSA camera and uses sensors and software to perform advanced GNC functions. Exploring ways to enhance space object characterization.

Developer:	AFRL	**Country:**	USA
First Use Date:	2018	**Status:**	Flown

Performance Parameters:

Contact:	N, free-flying
Inspection Type:	Visual
Resolution:	N/A
Inspection Aides / Fiducials / Cues:	SSA Camera, ADCS sensors/software
Data Analysis:	Autonomous

6.11.7 IM - 7: Programmable Josephson Voltage Standard (PJVS)

Description: PJVS stands for Programmable Josephson Voltage Standard. It is an intrinsic electrical DC Voltage Standard used internationally by national measurement institutes (NMI; e.g., NIST, PTB, NPL). Josephson junctions are used for traceability of voltage measurements to the SI (System International) unit of Voltage for all metrology.

Developer:	National Institute of Standards and Technology (NIST), NASA
Country:	USA
First Use Date:	2020
Status:	In Use

Performance Parameters:

Contact:	Y
Inspection Type:	Voltage
Resolution:	+/-0.02 ppm
Inspection Aides / Fiducials / Cues:	Liquid Helium ($1000/deployment)
Data Analysis:	Off-board

6.11.8 IM - 8: Robotic External Leak Locator (RELL)

Description: NASA's Robotic External Leak Locator (RELL) is a robotic, remote-controlled tool that helps mission operators detect the location of an external leak and rapidly confirm a successful repair.

Developer:	NASA GSFC	**Country:**	USA
First Use Date:	2015	**Status:**	Flown

Performance Parameters:

Contact:	Y, robot-arm
Inspection Type:	Ammonia sensor
Resolution:	High
Inspection Aides / Fiducials / Cues:	Mass spectrometer, Ion vacuum pressure gauge
Data Analysis:	Autonomous

6.11.9 IM - 9: Seeker

Description: 3U spacecraft that is deployed from Orbital ATK Enhanced Cygnus ISS resupply spacecraft. Performs 60-minute mission consisting of proximity operations around Cygnus. UT-developed vision system isolated from all other sensors onboard the spacecraft, using only a commercially available camera and state-of-the-art computer vision algorithms to detect Cygnus spacecraft.

Developer:	UT Austin/NASA JSC	**Country:**	USA
First Use Date:	2019	**Status:**	Flown

Performance Parameters:

Contact:	N, free-flying
Inspection Type:	Visual
Resolution:	High
Inspection Aides / Fiducials / Cues:	Elevation/Azimuth computation
Data Analysis:	Autonomous (2 Hz)

6.11.10 IM - 10: Sonatest Veo PAUT

Description: The Sonatest Veo PAUT system was chosen over several other phased array ultrasonic test (PAUT) devices as well as eddy current devices (EC) for attachment to the body of the ISS due to micrometeroids. By making contact between the device and the area of damage the device is able to find hidden structures such as isogrid webs that allows the team to determine what type of repair should be done.

Developer:	NASA	**Country:**	USA
First Use Date:	2013	**Status:**	Flown

Performance Parameters:

Contact:	Y
Inspection Type:	Ultrasonic
Resolution:	0.1 inches
Inspection Aides / Fiducials / Cues:	Multi-angle top scan
Data Analysis:	Off-board

6.11.11 IM - 11: Visual Inspection Poseable Invertebrate Robot (VIPIR)

Description: VIPIR, the Visual Inspection Poseable Invertebrate Robot, is a robotic, multi-capability inspection tool designed to deliver near and midrange inspection capabilities in space.

Developer:	NASA GSFC	**Country:**	USA
First Use Date:	2015	**Status:**	Flown

Performance Parameters:

Contact:	Y, Robot-arm
Inspection Type:	Visual
Resolution:	224 x 224 pixels, 100 degree Field of View
Inspection Aides / Fiducials / Cues:	8-24 mm optical zoom lens
Data Analysis:	Off-board

7 REFERENCES

7.1 ROBOTIC MANIPULATION

1. https://www.nasa.gov/mission_pages/tdm/osam-2.html
2. https://madeinspace.us/capabilities-and-technology/archinaut/
3. https://sbir.nasa.gov/SBIR/abstracts/21/sbir/phase1/SBIR-21-1-Z3.04-2593.html
4. https://www.nasa.gov/feature/langley/nasa-assemblers-are-putting-the-pieces-together-for-autonomous-in-space-assembly
5. https://en.wikipedia.org/wiki/Lunar_Gateway
6. https://www.canada.ca/en/space-agency/news/2020/06/building-the-next-canadarm.html
7. https://en.wikipedia.org/wiki/Dextre
8. https://directory.eoportal.org/web/eoportal/satellite-missions/e/ets-vii
9. https://en.wikipedia.org/wiki/European_Robotic_Arm
10. http://www.esa.int/Science_Exploration/Human_and_Robotic_Exploration/International_Space_Station/European_Robotic_Arm
11. Fleischner, Richard. "Insight Instrument Deployment Arm," *15th European Space Mechanisms & Tribology Symposium – ESMATS 2013*. September 25-27, 2013. URL: https://www.esmats.eu/esmatspapers/pastpapers/pdfs/2013/fleischner.pdf.
12. http://iss.jaxa.jp/en/kibo/about/kibo/rms/
13. https://www.tethers.com/robotic-arm/
14. https://www.nasa.gov/centers/langley/multimedia/iotw-lsms.html#.YBlytadKhPZ
15. https://mars.nasa.gov/mars2020/spacecraft/rover/arm/
16. Baumgartner, Eric T., Bonitz, Robert G., Melko, Joseph P., Shiraishi, Lori R., and Leger, P. Chris, "The Mars Exploration Rover Instrument Positioning System," 2005 IEEE Aerospace Conference, December 20, 2004, URL: https://www-robotics.jpl.nasa.gov/publications/Eric_Baumgartner/IPS_IEEE_Aerospace_2005_final.pdf.
17. Billing, Rius and Fleischner, Richard, "Mars Science Laborarory Robotic Arm," *14th European Space Mechanisms & Tribology Symposium – ESMATS 2011*. September 28-30, 2011. URL: https://www.esmats.eu/esmatspapers/pastpapers/pdfs/2011/billing.pdf.
18. Bonitz, Robert G., Nguyen, Tam T., and Kim, Won S., "The Mars Surveyor '01 Rover and Robotic Arm," IEEE Paper, 2000, URL: https://www-robotics.jpl.nasa.gov/publications/Tam_Nguyen/roverArm01.pdf.
19. Bonitz, Robert et al., "Mars Volatiles and Climate Surveyor Robotic," *Journal of Geophysical Research*, Vol. 106, No. E8, Pages 17,623-17,634, August 25, 2001, URL: https://agupubs.onlinelibrary.wiley.com/doi/pdf/10.1029/1999JE001140
20. https://nexis.gsfc.nasa.gov/robotic_servicing_arm.html
21. Ogilvie, Andrew, Allport, Justin, Hannah, Michael, and Lymer, John, "Autonomous Satellite Serving Using the Orbital Express Demonstration Manipulator System," i-SAIRAS 2008 Conference, URL: http://robotics.estec.esa.int/i-SAIRAS/isairas2008/Proceedings/SESSION%2014/m113-Ogilvie.pdf.

22. Bonitz, Robert et al., "The Phoenix Mars Lander Robotic Arm," IEEEAC Paper, December 15, 2008, URL:http://www-robotics.jpl.nasa.gov/publications/Richard_Volpe/z02_0104.pdf.
23. Akin, David, Roberts, Brian, Smith, Walt, and Sullivan, Brook, "University of Maryland Concepts and Technologies for Robotic Servicing of Hubble Space Telescope," Space Systems Laboratory at University of Maryland, URL: https://spacecraft.ssl.umd.edu/publications/GSFC.040402.pdf.
24. http://robonaut.jsc.nasa.gov/ISS/
25. Henshaw, Glen and Kelm, Bernard, "DARPA Phoenix: Overview and Risk Reduction Plans," i-SAIRAS 2014 Conference, URL: https://www.nasa.gov/sites/default/files/files/G_Henshaw-NRL_Advances_in_Orbital_Inspection.pdf
26. https://en.wikipedia.org/wiki/Canadarm
27. http://www.ieee.ca/millennium/canadarm/canadarm_technical.html
28. https://nexis.gsfc.nasa.gov/OSAM-1.html
29. https://spacenews.com/mda-robotics-for-spider-osam-1/
30. https://en.wikipedia.org/wiki/Mobile_Servicing_System
31. http://www.nasa.gov/mission_pages/station/structure/elements/mss.html
32. https://en.wikipedia.org/wiki/Strela_(crane)
33. https://www.nasa.gov/mission_pages/station/expeditions/expedition30/spacewalk.html
34. https://en.wikipedia.org/wiki/Mir
35. https://technology.nasa.gov/patent/LAR-TOPS-220
36. NASA Langley Research Center, "Human Robotic Systems: Tendon Actuated Lightweight In-Space Manipulators (TALISMAN)," NASA Facts, 2015, URL: https://www.nasa.gov/sites/default/files/atoms/files/fs_talisman_150908.pdf.

7.2 RPO, CAPTURE, DOCKING, AND MATING

37. https://aerospace.org/article/cubesats-get-close-proximity-operation-interesting-implications
38. Gangestad, J. W., Venturini, C. C., Hinkley, D. A., and Kinum, G., "A Sat-to-Sat Inspection Demonstration with the AeroCube-10 1.5U CubeSats," Small Satellite Conference, July 2021
39. https://www.kirtland.af.mil/Portals/52/documents/AFD-131204-039.pdf?ver=2016-06-28-105617-297
40. Weeden, B., and Samson, V., "Global Counterspace Capabilities," Secure World Foundation, April 2021, "https://swfound.org/media/207162/swf_global_counterspace_capabilities_2021.pdf"
41. Blain, C., van Binst, E. T., Gao, L., Xu, L., and Patil, V., 2017, "Is Space Market Ready for LEO Deorbiting Commercial Services?", Research Project for Master of Business Administration, Toulouse Business School, Toulouse, France, "https://chaire-sirius.eu/documents/dbe353-blain-et-al--2017.pdf"
42. https://nexis.gsfc.nasa.gov/argon.html
43. Galante, J. M., Van Eepoel, J., Strube, M., Gill, N., Gonzalez, M., Hyslop, A., Patrick, B., "Pose Measurement Performance of the Argon relative Navigation Sensor Suite in Simulated Flight Conditions," AIAA Guidance, Navigation, and Control Conference Paper, August 2012, https://ntrs.nasa.gov/api/citations/20120013578/downloads/20120013578.pdf

44. https://astroscale.com/astroscales-elsa-d-successfully-demonstrates-repeated-magnetic-capture/
45. *ELSA-d Press Kit,* Astroscale, 2021. URL: https://astroscale.com/wp-content/uploads/2021/08/ELSA-d-Press-Kit-2021.pdf
46. https://directory.eoportal.org/web/eoportal/satellite-missions/content/-/article/elsa-d
47. https://directory.eoportal.org/web/eoportal/satellite-missions/e/ets-vii
48. Kawano, I., Masaaki, M., Kasai, T., and Suzuki, T., “Result and Evaluation of Autonomous Rendezvous Docking Experiments of ETS-VII”, AIAA Guidance, Navigation, and Control Conference Paper, August 1999, https://arc.aiaa.org/doi/pdf/10.2514/6.1999-4073
49. https://www.tethers.com/in-space-services/
50. https://spacenews.com/tethers-unlimited-developing-satellite-servicer-for-leo-missions/
51. https://spacenews.com/northrop-grummans-mev-1-servicer-docks-with-intelsat-satellite/
52. https://news.northropgrumman.com/news/features/mission-extension-vehicle-breathing-life-back-into-in-orbit-satellites
53. https://www.northropgrumman.com/space/space-logistics-services/
54. https://space.skyrocket.de/doc_sdat/mev-1.htm
55. *MEV-2 Technical Appendix,* Space Logistics, LLC. URL: https://fcc.report/IBFS/SAT-LOA-20191210-00144/2098823.pdf
56. https://www.northropgrumman.com/space/space-logistics-services/
57. https://afresearchlab.com/technology/space-vehicles/mycroft/
58. *ESPA Augmented Geosynchronous Laboratory Experiment (EAGLE),* Air Force Research Laboratory, April 2018. URL: https://www.kirtland.af.mil/Portals/52/documents/EAGLE-factsheet.pdf
59. International Docking System Standard (IDSS) Interface Definition Document (IDD) Revision E, October 2016, https://ntrs.nasa.gov/api/citations/20170001546/downloads/20170001546.pdf
60. Christiansen, S., Nilson, T., “Docking System Mechanism Utilized on Orbital Express Program,” Aerospace Mechanisms Symposium, May 2008, https://www.esmats.eu/amspapers/pastpapers/pdfs/2008/christiansen.pdf
61. Shoemaker, James, Wright, Melissa, and Sivapiragasam, Sanjivan, "Orbital Express Space Operations Architecture Program," 17th Annual AIAA/USU Conference on Small Satellites, Paper SSC03-IV-2, 2003. URL: https://digitalcommons.usu.edu/cgi/viewcontent.cgi?referer=&httpsredir=1&article=1768&context=smallsat
62. https://earth.esa.int/web/eoportal/satellite-missions/s/stp-1
63. https://nexis.gsfc.nasa.gov/osam-1.html
64. https://nexis.gsfc.nasa.gov/Raven.html
65. Strube, M., Henry, R., Skelton, E., Van Eepoel, J., Gill, N., McKenna, R., “RAVEN: An On-Orbit Relative Navigation Demonstration Using International Space Station Visiting Vehicles,” Advances in the Astronautical Sciences Guidance, Navigation, and Control 2015, Vol. 154, 2015, https://ntrs.nasa.gov/api/citations/20150002731/downloads/20150002731.pdf

66. Roesler, G., “Robotic Servicing of Geosynchronous Satellites (RSGS) Proposers Day”, DARPA, May 2016, https://www.darpa.mil/attachments/RSGSProposersDaySlideDeck.PDF
67. Martin, M., Pfrang, K., and Weeden, B., “Chinese Military and Intelligence Rendezvous and Proximity Operations”, Secure World Foundation, April 2021, https://swfound.org/media/207179/swf_chinese_rpo_fact_sheet_apr2021.pdf
68. http://www.parabolicarc.com/2019/07/01/inspace-advanced-manufacturing/
69. https://data.nasa.gov/dataset/SOUL-System-Maturation-Phase-II/iuz7-g7y6
70. Hruby, V., DeLuccia, C., and Williams, D., “Tethered Robot for Spacecraft Self Inspection and Servicing,” AIAA SPACE Forum, September 2018. https://arc.aiaa.org/doi/pdf/10.2514/6.2018-5342
71. https://www.orbitfab.space/products
72. https://momentus.space/services/
73. Davis, T., Baker, T., Belchak, T., and Larsen, W., “XSS-10 Micro-Satellite Flight Demonstration Program,” AIAA/USU Conference on Small Satellites, August 2003. https://digitalcommons.usu.edu/cgi/viewcontent.cgi?article=1767&context=smallsat
74. https://www.kirtland.af.mil/Portals/52/documents/AFD-111103-035.pdf?ver=2016-06-28-110256-797
75. https://directory.eoportal.org/web/eoportal/satellite-missions/v-w-x-y-z/xss

7.3 RELOCATION

76. Stokes, M., Alvarado, G., Weinstein, E., and Easton, I., “China’s Space and Counterspace Capabilities and Activities,” The U.S.-China Economic and Security Review Commission, March 2020. https://www.uscc.gov/sites/default/files/2020-05/China_Space_and_Counterspace_Activities.pdf
77. https://spaceflight101.com/long-march-7-maiden-launch/aolong-1-asat-concerns/
78. https://astroscale.com/elsa-d/
79. https://directory.eoportal.org/web/eoportal/satellite-missions/content/-/article/elsa-d
80. https://www.northropgrumman.com/space/space-logistics-services/
81. https://www.northropgrumman.com/space/space-logistics-services/#:~:text=The%20Mission%20Extension%20Vehicle%2D1,whose%20fuel%20is%20nearly%20depleted
82. https://space.skyrocket.de/doc_sdat/mev-1.htm
83. https://www.northropgrumman.com/space/space-logistics-services/
84. https://space.skyrocket.de/doc_sdat/mev-1.htm
85. https://firefly.com/launch-suv/
86. https://momentus.space/services/
87. *Vigoride™ Transportation Service Datasheet,* Momentus, URL: https://www.satelliteconfers.org/wp-content/uploads/2020/05/Momentus_Vigoride-2.0-Datasheet-Final.pdf
88. https://www.dorbit.space/launch-deployment
89. https://spaceflight.com/sherpa/

7.4 PLANNED REPAIR, UPGRADE, MAINTENANCE, AND INSTALLATION

90. https://www.tethers.com/in-space-services/
91. Britton, Nathan, "Tethers Robotics," *International Conference on Intelligent Robots and Systems (IROS) 2020*. URL: https://hq.wvrtc.com/iros2020/invited-speakers/britton.pdf
92. https://altius-space.com/technologies.html
93. https://www.altius-space.com/blog/voyager-subsidiary-altius-space-machines-inc-announces-successful-first-orbital-launch-of-dogtags-aboard-onewebs-satellites/
94. https://www.spaceworks.aero/orbital/fuseblox/
95. https://www.oceaneering.com/brochures/gold-connectors/
96. *Bartolomeo User Guide, Issue 1*. Airbus, November 2018. URL: https://www.unoosa.org/documents/pdf/psa/hsti/Bartolomeo/BTL-UG.pdf
97. "External Payloads Proposer's Guide to the International Space Station," NASA Johnson Space Center International Space Station Program, SSP-51071 Baseline, August 2017. URL: https://explorers.larc.nasa.gov/HPMIDEX/pdf_files/07A_External-Payloads-Proposers-Guide-to-ISS-SSP-51071-Baseline_Redacted.pdf
98. "HOTDOCK: A Multifunctional Coupling Interface for Space & Non-Space Applications," HOTDOCK Product Sheet, Space Applications Services. URL: https://www.spaceapplications.com/wp-content/uploads/2019/05/7-product-sheet-hotdock-1.pdf
99. https://www.researchgate.net/publication/344871896_MOSAR-WM_A_relocatable_robotic_arm_for_future_on-orbit_applications
100. https://www.novawurks.com/services/about-hisat/
101. "NovaWurks/CONFERS One-Pager," CONFERS, 2018. URL: https://www.satelliteconfers.org/wp-content/uploads/2018/10/CONFIRS-One-Pager.pdf
102. http://www.iboss-satellites.com/iboss/
103. Kreisela, Joerg, Schervanb, Thomas A., and Schroederc, Prof. Dr. Kai-Uwe, "A Game-Changing Space System Interface Enabling Multiple Modular and Building Block-Based Architectures for Orbital And Exploration Missions," 70th International Astronautical Congress (IAC), IAC-19-D3.2B.6x54237, October 21-25, 2019. URL: https://www.iboss.space/wp-content/uploads/2019/11/IAC-19-Paper.pdf
104. https://altius-space.com/technologies.html
105. Christiansen, Scott and Nilson, Troy, Docking System Mechanism Utilized on Orbital Express Program," 39th Aerospace Mechanisms Symposium, May 79, 2008. URL: https://www.esmats.eu/amspapers/pastpapers/pdfs/2008/christiansen.pdf
106. Shoemaker, James, Wright, Melissa, and Sivapiragasam, Sanjivan, "Orbital Express Space Operations Architecture Program," 17th Annual AIAA/USU Conference on Small Satellites, Paper SSC03-IV-2, 2003. URL: https://digitalcommons.usu.edu/cgi/viewcontent.cgi?referer=&httpsredir=1&article=1768&context=smallsat
107. https://earth.esa.int/web/eoportal/satellite-missions/s/stp-1

108. Hruby, Vlad, DeLuccia, Craig, and Williams, Dan, “Tethered Robot for Spacecraft Self Inspection and Servicing,” 2018 AIAA SPACE Forum, September 17-19, 2018. URL: https://arc.aiaa.org/doi/pdf/10.2514/6.2018-5342
109. Vinals, Javier et al., “Multi-Functional Interface for Flexibility and Reconfigurability of Future European Space Robotics Systems,” 2018. URL: https://strathprints.strath.ac.uk/65962/1/Vinals_etal_AAST_2018_Multi_functional_interface_for_flexibility_and_reconfigurability_of_future_european.pdf
110. https://www.obruta.com/products

7.5 Unplanned or Legacy Repair and Maintenance

111. https://www.tethers.com/in-space-services/
112. https://spacenews.com/tethers-unlimited-developing-satellite-servicer-for-leo-missions/
113. https://www.northropgrumman.com/space/space-logistics-services/
114. https://www.satellitetoday.com/innovation/2021/04/12/northrop-grumman-successfully-docks-second-mission-extension-vehicle-with-operational-intelsat-satellite/
115. https://www.northropgrumman.com/space/space-logistics-services/
116. https://nexis.gsfc.nasa.gov/OSAM-1.html
117. https://www.nasa.gov/image-feature/goddard/2021/nasa-s-on-orbit-servicing-assembly-and-manufacturing-1-mission-ready-for-spacecraft
118. https://directory.eoportal.org/web/eoportal/satellite-missions/o/osam-1
119. https://nexis.gsfc.nasa.gov/robotic_refueling_mission.html
120. https://nexis.gsfc.nasa.gov/rrm_phase1.html
121. https://earth.esa.int/web/eoportal/satellite-missions/i/iss-rrm

7.6 Refueling and Fluid Transfer

122. Chato, David J., “Technologies for Refueling Spacecraft On-Orbit,” AIAA Paper No. 2000-5107 and NASA TM-2000-210476, November 2000. URL: https://ntrs.nasa.gov/citations/20000121212
123. https://www.orbitfab.space/products
124. https://spacenews.com/orbit-fab-demonstrates-satellite-refueling-technology-on-iss/
125. https://www.nasa.gov/directorates/spacetech/solicitations/tipping_points/2020_selections
126. Kirkland, Z. and Tegart, J.,"On-orbit Propellant Resupply Demonstration," AIAA Paper No. 84-1342, June 1984. URL: https://arc.aiaa.org/doi/abs/10.2514/6.1985-1233
127. Espero, Tracey, “Orbital Express: A New Chapter In Space,” Presentation to NASA Future In-Space Operations (FISO) Working Group, March 2007. URL: http://fiso.spiritastro.net/telecon07-09/Espero_3-28-07/
128. *Reference Guide to the International Space Station – Utilization Edition*, NP-2015-05-022-JSC, September 2015. https://www.nasa.gov/sites/default/files/atoms/files/np-2015-05-022-jsc-iss-guide-2015-update-111015-508c.pdf
129. https://www.nasa.gov/mission_pages/station/structure/elements/progress_about.html

130. Tiffin, Daniel J., “Orbital Fueling Architectures Leveraging Commercial Launch Vehicles for More Affordable Human Exploration,” Master of Science Thesis at Case Western Reserve University, January 2020. URL: https://etd.ohiolink.edu/apexprod/rws_etd/send_file/send?accession=case1575590285930015&disposition=inline
131. Stokes, Mark et al., *China’s Space and Counterspace Capabilities and Activities*, Report for U.S.-China Economic and Security Review Commission, March 30, 2020. URL: https://www.uscc.gov/sites/default/files/2020-05/China_Space_and_Counterspace_Activities.pdf
132. https://www.chinadaily.com.cn/china/2016-07/04/content_25954551.htm

7.7 STRUCTURAL MANUFACTURING AND ASSEMBLY

133. https://madeinspace.us/capabilities-and-technology/archinaut/
134. https://redwirespace.com/product/archinaut/
135. https://madeinspace.us/blog/press-releases/first-ever-3d-printing-in-a-space-like-environment-demonstrated/
136. https://www.nasa.gov/mission_pages/tdm/osam-2.html
137. https://madeinspace.us/capabilities-and-technology/archinaut/
138. https://motivss.com/products-capabilities/xlink/
139. https://www.nasa.gov/feature/langley/nasa-assemblers-are-putting-the-pieces-together-for-autonomous-in-space-assembly
140. https://sbir.gsfc.nasa.gov/SBIR/abstracts/12/sbir/phase2/SBIR-12-2-H5.01-9689.html
141. Levedahl, B., Hoyt, R., Gorges, J., Silagy, T., Britton, N., Jimmerson, G., Bodnar, M., and Slostad, J., “Trusselator™ Technology for In-Situ Fabrication of Solar Array Support Structures,” AIAA SciTech Forum, January 2018.
142. Card, M.F., Heard, W.L., and Akin, D.L., “Construction and Control of Large Space Structures,” NASA TM-87689, February 1986.
143. Doggett, W.R., Dorsey, J.T., Ganoe, G.G., King, B.D., Jones, T.C., Mercer, C.D., and Corbin, K., “Hinge for Use in a Tension Stiffened and Tendon Actuated Manipulator Patent”, US Patent 9,168,659, 2013.
144. https://www.nasa.gov/image-feature/langley/engineers-test-space-erector-set/
145. https://www.nasa.gov/mission_pages/tdm/irma/orbital-atk-supports-ground-testing-on-ciras-at-nasa-s-langley-research-center.html
146. https://technology.nasa.gov/patent/LAR-TOPS-316
147. Doggett, W.R, King, B.D., Dorsey, J.T., Hales, S.J., and Domack, C.S., “Robotically Compatible Erectable Joint with Noncircular Cross Section”, US Patent Publication Number: 20200124071, April 2020.
148. https://technology.nasa.gov/patent/LAR-TOPS-268
149. https://nexis.gsfc.nasa.gov/OSAM-1.html
150. *SPIDER Handout,* MAXAR, September 2020. URL: https://cdn.mediavalet.com/usva/maxar/z8uIlxbV1U29PHN9aCq_wA/yiUZqbkemEGjy0lRUSB3GA/Original/60004-handout-spider-09-2020.pdf

151. https://technology.nasa.gov/patent/LAR-TOPS-198

7.8 RECYCLING, REUSE, AND REPURPOSING

152. Prater, Tracie et al., "NASA's In-Space Manufacturing Project: Update on Manufacturing Technologies and Materials to Enable More Sustainable and Safer Exploration," *70th Annual International Astronautical Congress*, October 25, 2019, URL: https://ntrs.nasa.gov/api/citations/20190033332/downloads/20190033332.pdf
153. https://data.nasa.gov/dataset/Metal-Advanced-Manufacturing-Bot-Assisted-Assembly/7v9h-vp2q/data?no_mobile=true
154. Prater, Tracie et al., "In-Space Manufacturing: Using the International Space Station (ISS) as a Test Bed," ISS Research and Development Conference 2020, August 2020. URL: https://ntrs.nasa.gov/citations/20205006790
155. https://www.nasa.gov/oem/inspacemanufacturing
156. "Reclaimable Thermally Reversible Polymers for AM Feedstock," SBIR Proposal Summary, URL: https://sbir.nasa.gov/SBIR/abstracts/16/sbir/phase1/SBIR-16-1-H5.04-8148.html

7.9 PARTS AND GOODS MANUFACTURING

157. Prater, Tracie et al., "NASA's In-Space Manufacturing Project: Update on Manufacturing Technologies and Materials to Enable More Sustainable and Safer Exploration," 70th Annual International Astronautical Congress, October 25, 2019, URL: https://ntrs.nasa.gov/api/citations/20190033332/downloads/20190033332.pdf
158. Prater, Tracie et al., "3D Printing in Zero G Technology Demonstration Mission: Complete Experimental Results and Summary of Related Material Modeling Efforts," International Journal of Advanced Manufacturing Technology, March 2019.
159. *Additive Manufacturing Facility (AMF) User Guide,* Made in Space, April 29, 2016. URL: https://madeinspace.us/wp-content/uploads/2019/07/AMFuserguide-1.pdf
160. Prater, Tracie et al., "NASA's In-Space Manufacturing Project: Toward a Multimaterial Fabrication Laboratory for the International Space Station," Proceedings of the AIAA SPACE Conference. September 2017.
161. Prater, T.J., N. Werkheiser, F. Ledbetter, Kristin, Morgan "In-Space Manufacturing at NASA Marshall Space Flight Center: A Portfolio of Fabrication and Recycling Technology Development for the International Space Station." Submitted to AIAA SPACE 2018.
162. Prater, Tracie et al., "In-Space Manufacturing: Using the International Space Station (ISS) as a Test Bed," ISS Research and Development Conference 2020, August 2020. URL: https://ntrs.nasa.gov/citations/20205006790
163. *In-Space Manufacturing (ISM) Overview,* NASA Marshall Space Flight Center, 2019. URL: https://ntrs.nasa.gov/api/citations/20190033503/downloads/20190033503.pdf
164. https://redwirespace.com/2021/07/29/redwire-to-demonstrate-in-space-additive-manufacturing-for-lunar-surface-on-the-international-space-station/
165. https://madeinspace.us/capabilities-and-technology/vulcan/
166. https://SBIR.nasa.gov

7.10 SURFACE CONSTRUCTION

167. https://www.nasa.gov/oem/surfaceconstruction
168. https://www.3dprintingmedia.network/ai-spacefactory-wins-500000-nasa-3d-printed-habitat-challenge-first-prize/
169. Mueller, R.P., Fikes, J.C., Case, M.P., Khoshnevis, B., Fiske, M.R., Edmunson, J.E., Kelso, R., Romo, R., and Andersen, C., "Additive Construction with Mobile Replacement (ACME)", *68th International Astronautical Congress*, Sep 2017, URL: https://www.researchgate.net/publication/322567924_Additive_Construction_with_Mobile_Emplacement_ACME
170. https://www.nasa.gov/directorates/spacetech/game_changing_development/projects/armadas
171. "Space Technology Game Changing Development: Automated Reconfigurable Mission Adaptive Digital Assembly Systems (ARMADAS)", *NASAfacts* FS-2018-04-05-ARC, URL: https://www.nasa.gov/sites/default/files/atoms/files/armadas_fs-final-3-08-19.pdf
172. https://www.nasa.gov/chapea
173. https://www.nasa.gov/feature/nasa-kennedy-to-develop-tech-to-melt-moon-dust-extract-oxygen
174. Mueller, R.P., Wilkinson, R.A., Gallo, C.A., Nick, A.J., Shuler, J.M., and King, R.H., "Lightweight Bulldozer Attachment for Construction and Excavation on the Lunar Surface", *AIAA Paper 2009-6466*, Sep 2009, URL: https://arc.aiaa.org/doi/pdf/10.2514/6.2009-6466
175. Jones, Thomas C., "Lightweight Surface Manipulation System (LSMS) Overview for Blue Origin", Space Technology Mission Directorate – Lunar Surface Innovation Institute (LSII), NASA Langley Research Center – Structural Mechanics and Concepts Branch, August 21, 2020, URL: https://ntrs.nasa.gov/api/citations/20205006977/downloads/LSMS%20Technology%20Overview%20V5%20Blue%20Origin.pdf
176. https://technology.nasa.gov/patent/LAR-TOPS-73
177. https://govtribe.com/opportunity/federal-contract-opportunity/moon-to-mars-planetary-autonomous-construction-technology-mmpact-80msfc
178. https://technology.nasa.gov/patent/KSC-TOPS-7
179. Mueller, R.P., Cox, R.E., Ebert, T., Smith, J.D., Schuler, J.M., and Nick, A.J., "Regolith Advanced Surface Systems Operations Robot (RASSOR)", *2013 IEEE Aerospace Conference*, Mar 2013, URL: https://ieeexplore.ieee.org/stamp/stamp.jsp?tp=&arnumber=6497341
180. https://www.aispacefactory.com/marsha
181. Prater, Tracie et al., "In-Space Manufacturing: Using the International Space Station (ISS) as a Test Bed," *ISS Research and Development Conference 2020*, August 2020. URL: https://ntrs.nasa.gov/citations/20205006790

7.11 INSPECTION AND METROLOGY:

182. https://aerospace.org/article/cubesats-get-close-proximity-operation-interesting-implications
183. https://ams02.space/detector

184. https://www.kirtland.af.mil/Portals/52/documents/AFD-131204-039.pdf?ver=2016-06-28-105617-297
185. JSC/ES2/Studor, George, "In-Space Inspection Technologies Vision", *Workshop Session 1 and 4*, Feb 29, 2012, URL: https://ntrs.nasa.gov/api/citations/20120003249/downloads/20120003249.pdf
186. https://rogue.space/orbots/
187. https://afresearchlab.com/technology/space-vehicles/mycroft/
188. https://aviationweek.com/defense-space/space/spotlight-satellite-servicing
189. Fortier, Michael, "Overview of NASA's Shared PJVS", Feb 19, 2021, URL: https://sma.nasa.gov/docs/default-source/sma-disciplines-and-programs/metcal/overview-of-nasa-s-shared-pjvs-final-002-508.pdf
190. https://sites.utexas.edu/tsl/seeker/
191. https://ntrs.nasa.gov/citations/20140000802
192. Davis, T.M., Baker, T.L., Belchak, T.A., and Larsen, W.R., "XSS-10 Micro-Satellite Flight Demonstration Program", *17th Annual AIAA/ISU Conference on Small Satellites* Paper Number SSC03-1-IV-1, August 2003, URL: https://digitalcommons.usu.edu/cgi/viewcontent.cgi?article=1767&context=smallsat
193. "XSS-11 Micro Satellite", *Fact Sheet*, AFRL Space Vehicles Directorate, Sept 2011, URL: https://www.kirtland.af.mil/Portals/52/documents/AFD-111103-035.pdf?ver=2016-06-28-110256-797
194. https://nexis.gsfc.nasa.gov/rrm_phase2vipir.html
195. https://nexis.gsfc.nasa.gov/rell.html