In-space Servicing, Assembly, and Manufacturing (ISAM) State of Play

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A document to characterize the current state of ISAM 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 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.

In-space Servicing, Assembly, and Manufacturing (ISAM) can vastly expand the performance, availability, and lifetime of space systems compared to the traditional paradigm of launching an asset with no intent to ever touch it again. ISAM capabilities 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, power generation, and reusability.

Previous achievements in ISAM have enabled ambitious human and robotic space missions. NASA's International Space Station (ISS) operations and maintenance, servicing missions of the Hubble Space Telescope (HST), and Northrop Grumman's Mission Extension Vehicle (MEV) demonstrate the dramatic operational missions that can be achieved using ISAM capabilities. Many current and upcoming 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 ISAM missions, capabilities, and developments. Compiling and organizing the available ISAM capabilities will help mission designers incorporate ISAM 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 ISAM capabilities into 11 capability areas that describe the functions or activities that would be performed in space using ISAM.

- **Robotic Manipulation**: Robotic manipulators have flown on a variety of missions, from surface robotics on Mars to long reach manipulation on ISS. Many more 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 ISAM 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 ISAM 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 ISAM ecosystem where the client spacecraft and ISAM 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 valuable. 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 that enable constructing 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-based 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 client 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.

This version of the *ISAM State of Play* is part of a continuing journey to encourage the use of ISAM capabilities in space. Compiling and organizing the current state of ISAM provides a simple resource for those working in the ISAM 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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Acronyms and abbreviations used in the document are defined below.

AC-10	Aerocube-10
ACCESS	Assembly Concept for Erectable Space Structures
ACME	Additive Construction with Mobile Emplacement
AFRL	Air Force Research Laboratory
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
CHAPEA	Crew Health and Performance Analog
CNC	Computerized Numerical Control
DARPA	Defense Advanced Research Projects Agency
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
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
ISAM	In-space Servicing, Assembly, and Manufacturing
ISFR	In-Situ Fabrication and Repair
ISM	In-Space Manufacturing
ISRU	In-situ Resource Utilization
ISS	International Space Station
ISSI	Intelligent Space System Interface
JEM	Japanese Experiment Module
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
MRV	Mission Robotic Vehicle
MSG	Microgravity Science Glovebox
MVACS	Mars Volatiles and Climate Surveyor Robotic Arm
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
SPHERES	Synchronized Position Hold Engage and Reorient Experimental Satellite
SPIDER	Space Infrastructure Dexterous Robot
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.

ISAM is an emerging set of capabilities that enables inspection, repair, upgrade, modular assembly, and construction of space assets. This set of capabilities is also referred to as On-orbit Servicing, Assembly, and Manufacturing, or OSAM.

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.

ISAM can vastly expand the performance, availability, and lifetime of space systems compared to the traditional paradigm. Incorporating these ISAM capabilities could decrease upfront cost, introduce pay-as-you-go options for deploying space assets, and enable spacecraft larger than launch vehicle fairing dimensions. ISAM capabilities will 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 ISAM missions, capabilities, and developments. Understanding where these capabilities currently stand will help mission designers incorporate ISAM 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 ISAM is broad, and they are unlikely to have captured everything that has been or is being done in the area. As a result, new versions of the ISAM *State of Play* will be released periodically, and the community is encouraged to submit suggestions, corrections, and comments to the authors via email at LARC-DL-ISAM-SOP@mail.nasa.gov.

2 HISTORY OF ISAM

While ISAM is an emerging set of capabilities, previous use of ISAM enabled ambitious space missions. The assembly and maintenance of the ISS, the repair of the Alpha Magnetic Spectrometer instrument, the servicing missions of the HST, and the success of Northrop Grumman's MEV demonstrate the dramatic missions that can be achieved using ISAM capabilities. Many current and upcoming 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 a selection of the major operational missions that use ISAM and flight demonstrations that have advanced ISAM capabilities. After Hubble was launched in 1990, five Space Shuttle missions flew to the orbiting observatory for EVA astronaut repair and upgrade of the system in space. Japan launched the ETS-VII to demonstrate robotic servicing and it was the first satellite equipped with a robotic arm. Orbital Express was a joint DARPA and NASA mission that demonstrated RPO, refueling, and module replacement.

The ISS was assembled and serviced over multiple flights, spanning 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 RRM experiments 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. Aboard the ISS, NASA's ISM project has been able to demonstrate many manufacturing capabilities inside the pressurized volume.

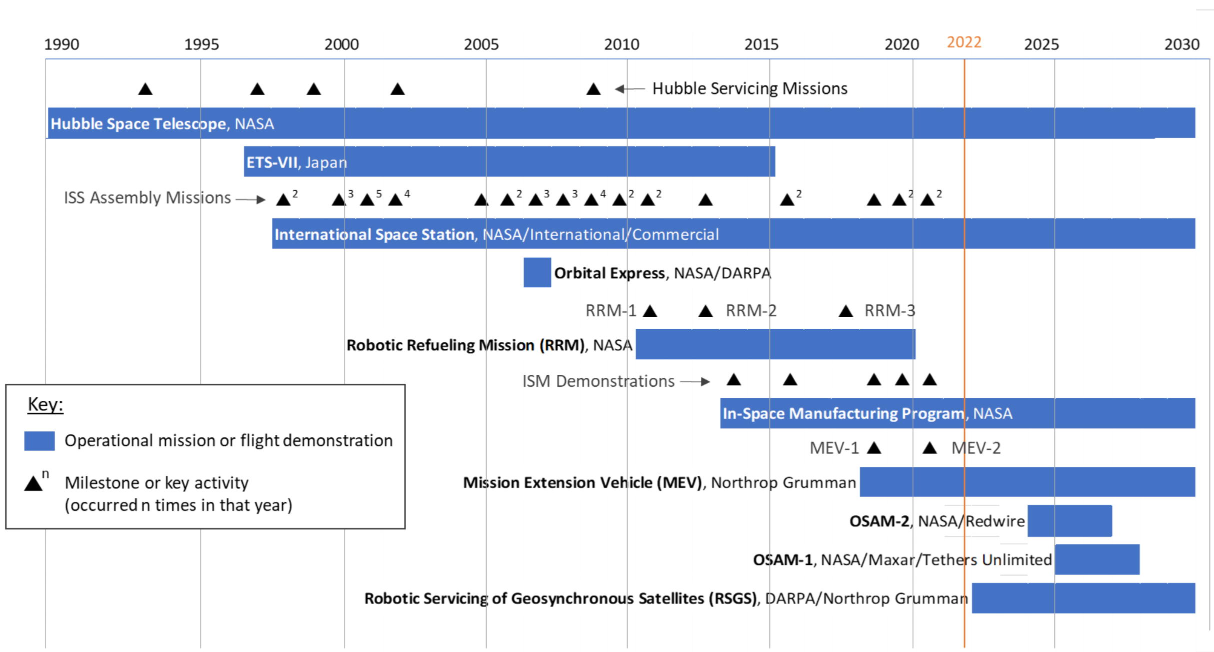

Figure 1: There is a long history of ISAM capabilities being used and advanced in ambitious operational missions (e.g., ISS, Hubble, and MEV) and flight demonstrations (e.g., Orbital Express). These missions and demonstrations have been performed by civil, national security, and commercial space organizations.

3 ISAM CAPABILITY AREAS

This document divides the ISAM capabilities into 11 capability areas that describe the functions or activities that would be performed in space using ISAM. These capability areas are distinct activities that an ISAM 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 lunar or planetary surface.
- **Structural Manufacturing and Assembly**: Involves creating or assembling structures in space to create spacecraft components or subsystems. Includes manufacturing (e.g., 3-D printing, extruding) 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 lunar or 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 (e.g., landing pads, roads) and vertical (e.g., power, habitation) 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. Table 1 in the Appendix breaks down the specific activities or subsystems from each mission that demonstrated the capability areas identified in Figure 2. The capability areas that have been incorporated the most are Inspection and Metrology; RPO, Capture, Docking, and Mating; and Robotic Manipulation. Through its assembly and servicing missions, the ISS uses the most ISAM capabilities that have heavily involved astronauts. The ISS has also been a platform that supports other demonstration missions (e.g., RRM demonstrations and the ISM project) that advance capabilities in ISAM and other areas. Technologies in every capability area have been used or demonstrated on orbit.

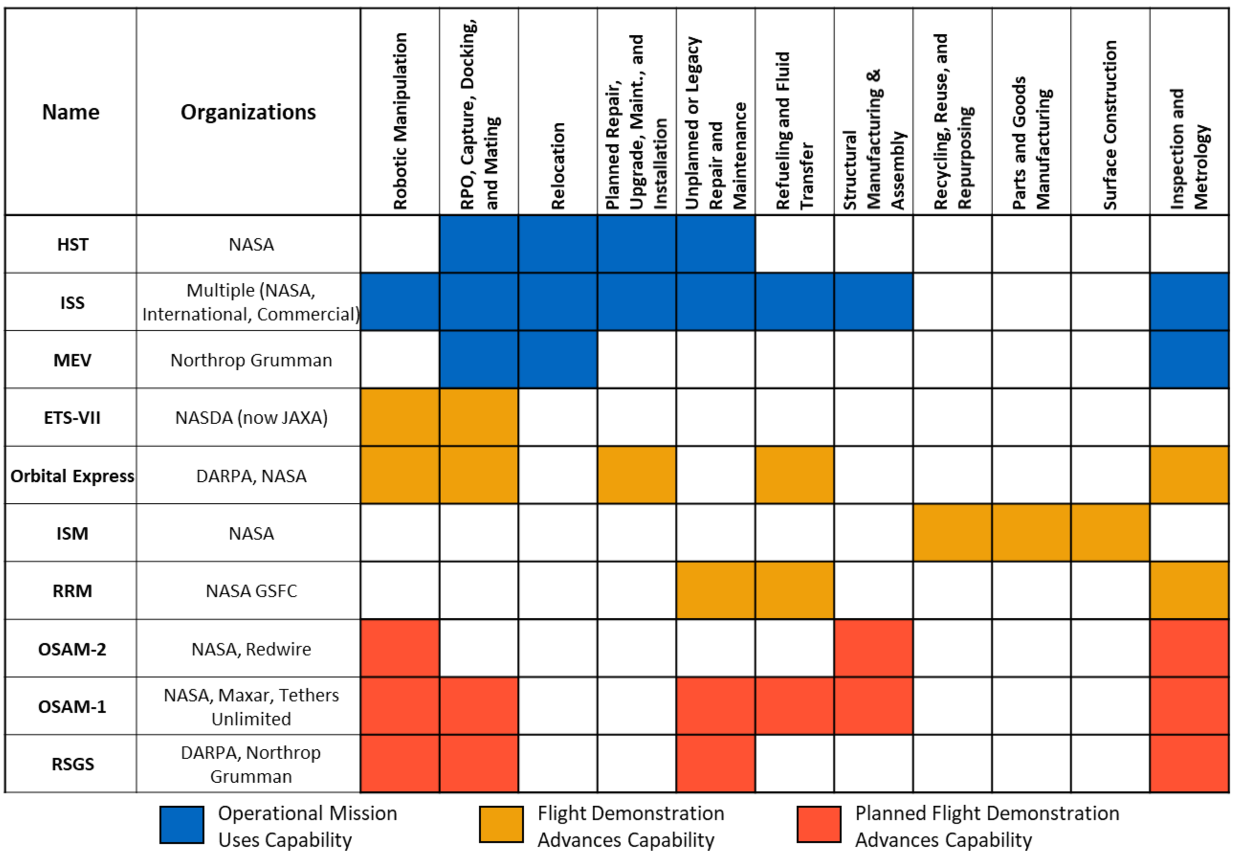

Figure 2: Operational missions and flight demonstrations have used and advanced ISAM capabilities, and planned missions will demonstrate more. Robotic Manipulation; RPO, Capture, Docking, and Mating; and Inspection and Metrology capability areas have been used in most of these missions, and the ISS has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

This document collects previous and ongoing ISAM development activities and technologies to describe the current state of ISAM. 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.

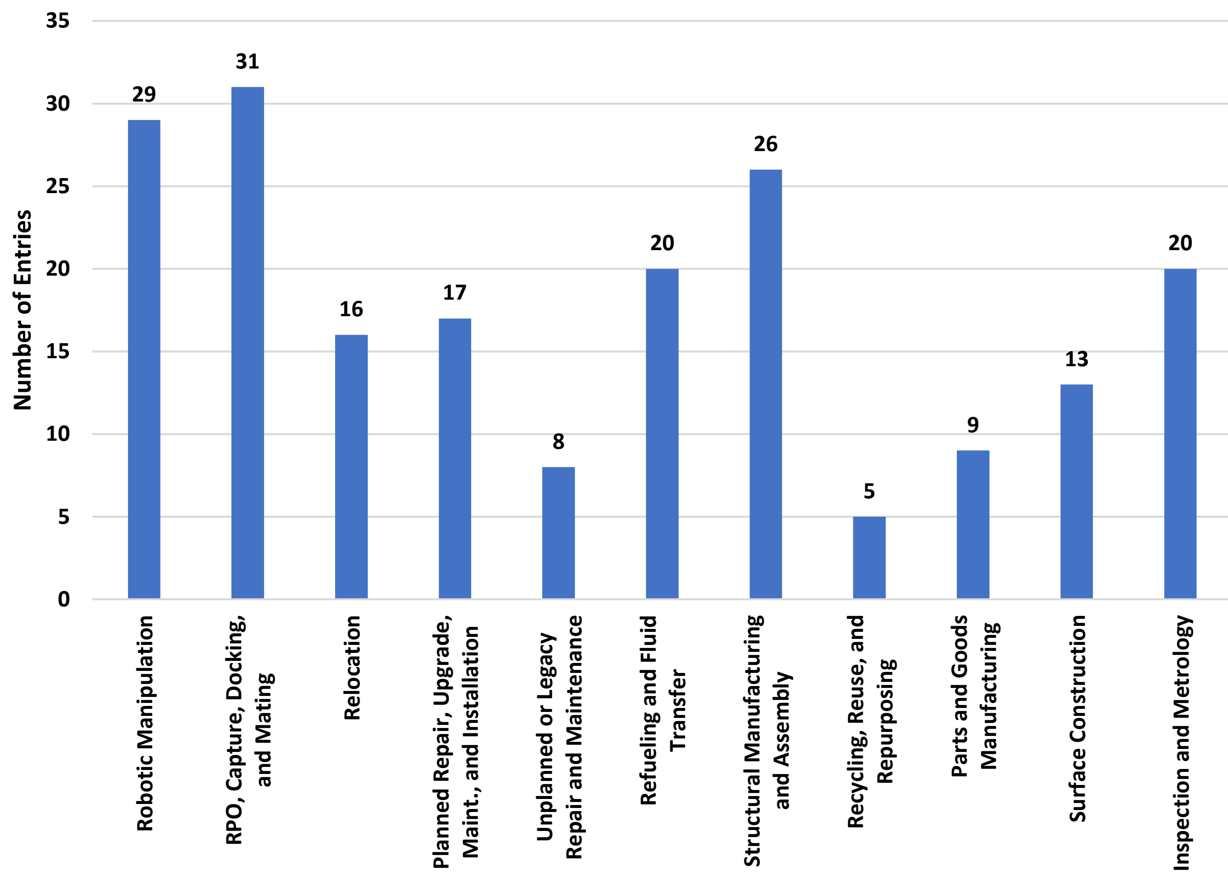

Figure 3: The activities or technologies collected in this document are categorized into the capability areas. This bar chart represents the number of activities in each capability area.

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, have been 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 parts, payloads, subsystems, or 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, move and arrange components for in-space assembly, and assist in the 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 its utility. 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 spacecraft in microgravity and on surface systems like landers and rovers. It was determined that 8 meters was a suitable discriminator between long and short reach manipulators due to the clustering of manipulators above and below 8 meters and the difference in use cases between the two divided groups. A summary of the robotic arms that have flown and that are currently under development is presented in Figure 4.

Long reach manipulators such as the SRMS and SSRMS, known as Canadarm and Canadarm2 respectively, have supported NASA's human space exploration missions since 1981. These robotic manipulators are teleoperated and support end effectors that attach to common grapple fixtures.

Short reach manipulators such as Dextre and JAXA SFA have been used to support servicing activities and experiments aboard the ISS. Both Dextre and the 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 categories within the robotic manipulation capability area. Planned long reach manipulators, such as TALISMAN, would provide high packing efficiency robotic arm options for microgravity operations. On the surface, extreme environments (e.g., dust, temperature, lighting conditions) are the driving requirements of manipulators like LSMS for payload offloading and handling and surface operations. Several short reach manipulators are in development such as the NASA Servicing Arm and the FREND arm to support servicing, assembly, and manufacturing technologies. ARMADAS, a current development at NASA Ames Research Center, is developing two mobile short reach robots for in-space assembly of standardized modules. Like Canadarm, the short reach ARMADAS robotic arms are designed to reposition throughout the assembled structure. Commercially, the trend in robotic manipulation is moving away from expensive, bespoke, human-operated manipulators and towards proliferated robotics in space with low cost, autonomous operations that will support future ISAM needs.

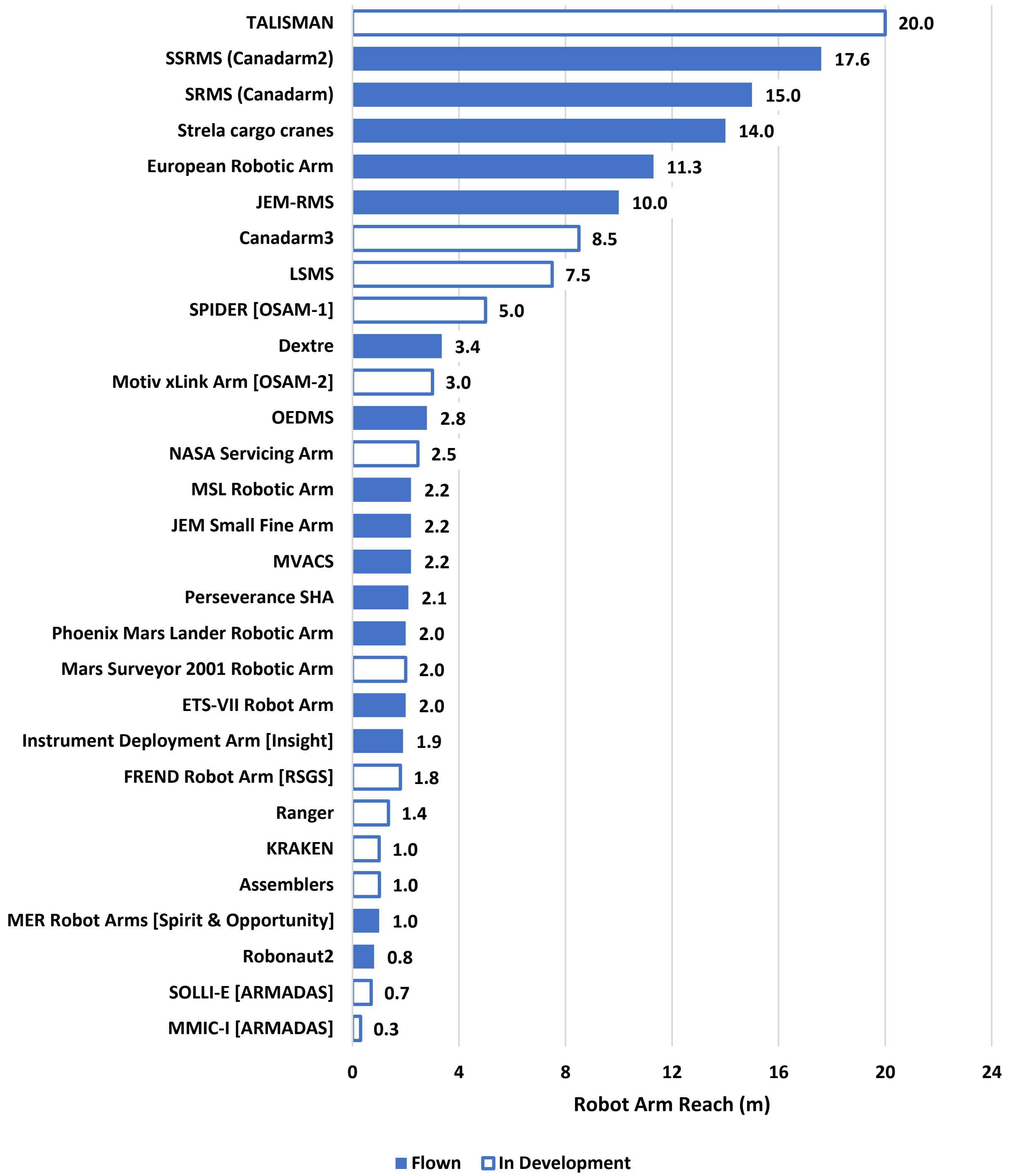

Figure 4: Robotic manipulators have flown for a variety of missions, from surface robotics to long reach manipulation on the ISS. Many are being developed to increase autonomy, reduce cost, and proliferate the use of space robotics. This figure displays the baseline configuration length for variable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

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 interaction between satellites 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, Cargo Dragon, and Crew Dragon.

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. The Hubble Space Telescope Servicing Mission 4 (2009) demonstrated RPO imaging during rendezvous between the HST and Space Shuttle, and the SRMS was used to grapple and release the HST. The ISS Raven Payload, which is still on-orbit, tracked vehicles visiting the ISS from 2017-2019 with three sensors (visible, infrared, lidar) to develop and test relative navigation capabilities.

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 and Starfish Space's Otter. The 200 kg (approximately) Otter space tug will include the Nautilus capture mechanism, capable of adhering to a broad array of space objects without the need of a prebuilt docking interface. 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. Figure 5 also highlights the distribution of contact versus non-contact missions. Contact includes any physical interaction with the target satellite while non-contact refers to only observational interaction, such as RPO.

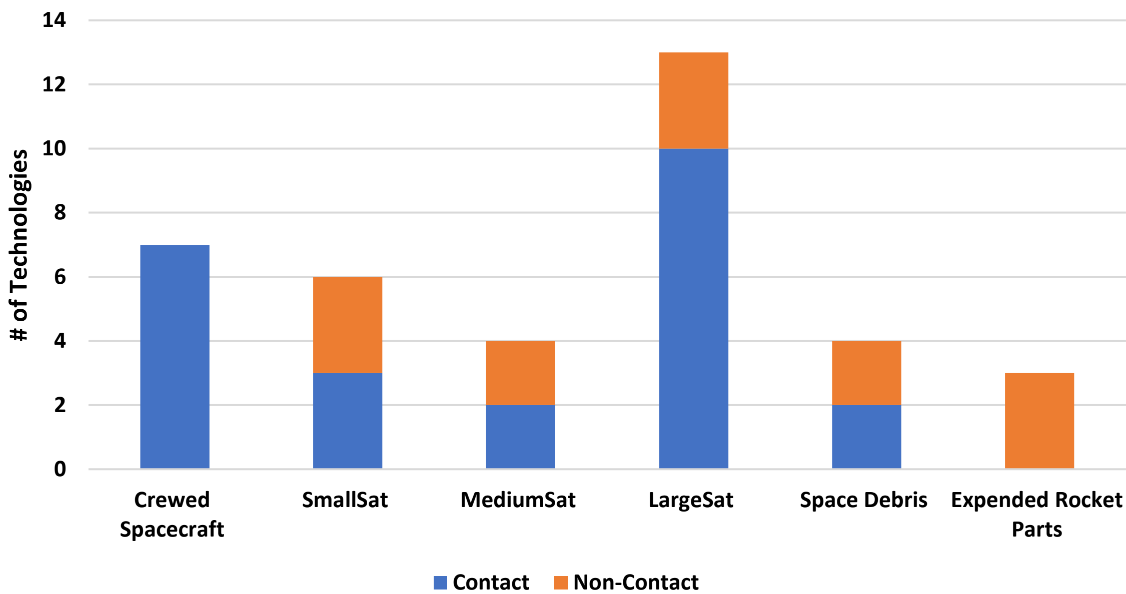

Figure 5: RPO, capture, docking, and mating technologies are useful for a wide range of client types. While most interest is focused on interaction with active satellites, this capability area is also used for managing expanded components or space debris. LargeSat includes spacecraft over 1000 kg, MediumSat includes spacecraft between 500-1000 kg, and SmallSat includes spacecraft less than 500 kg. Note: LargeSat technologies include HST servicing missions.

3.3 Relocation

Relocation refers to the capability of one spacecraft to alter the orbital parameters or orientation of another spacecraft. 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, Japan's ELSA-d mission was focused on the relocation of end-of-life satellites from an active orbit to a graveyard orbit. The ELSA-d mission demonstrated the capture of satellite space debris in 2022. Similarly, OSAM-1's baseline mission plan is to provide the capability to raise the client (Landsat-7) orbit prior to release of the spacecraft.

In addition to development of space debris removal technologies, relocation technology has also been developed through mission extension style missions. Northrop Grumman's MEV spacecraft currently provide mission extension services to commercial payloads. Planned mission extension spacecraft include Northrop Grumman's MEP and Starfish Space's Otter. These mission extension type satellites are ideal in situations where a client satellite is still functional but has lost the ability to modify its orbit due to propellant exhaustion or thruster failure. Instead of full satellite replacement, customers may instead extend the operational life of the satellite through the services of an on-orbit mission extension spacecraft. While MEV-1 and MEV-2 are both currently operating on orbit, MEP is currently in development and will interact with the MRV spacecraft which launches in 2024. The Northrop Grumman satellite lifetime extension spacecraft and the Starfish Space Otter space tug are designed to offer satellite mission extension in GEO. Otter will also provide end-of-life deorbiting services to satellites in LEO.

Current development in this capability area is also heavily focused on space tugs, 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 in development by MOOG and Firefly Aerospace, while Momentus' Vigoride and Launcher's Orbiter are being developed as rideshare options.

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

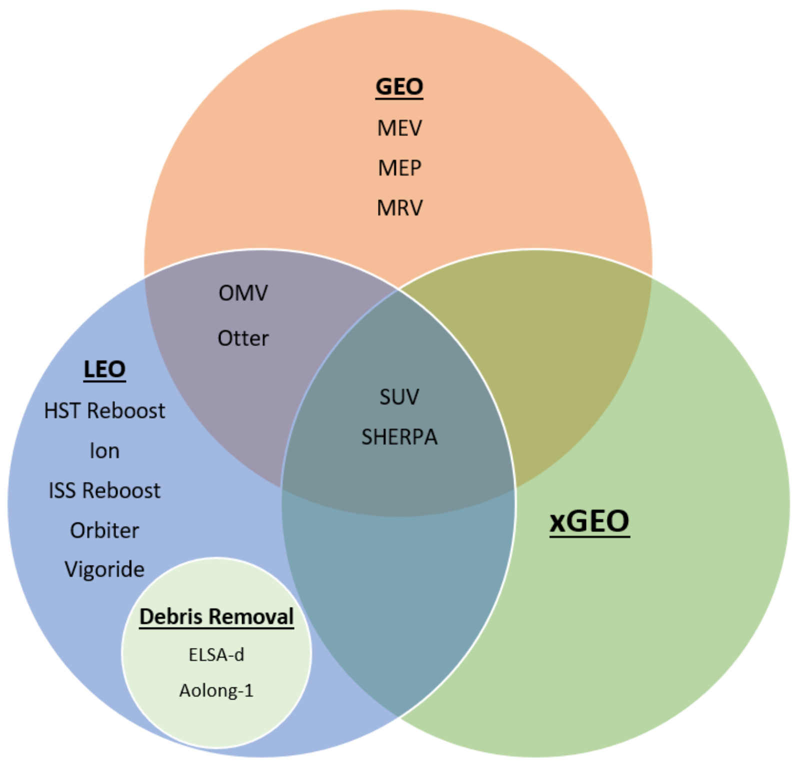

Figure 6: Relocation capabilities are currently heavily focused on LEO and GEO orbital regimes, and on commercial spacecraft targets. Of the technologies included in this figure, Aolong-1, ELSA-d, HST reboost, Ion, ISS reboost, MEV, and SHERPA have been demonstrated on orbit. Progress has been made towards relocation of orbital debris in LEO through the ELSA-d and Aolong-1 missions, and future capabilities in xGEO space are in development through Firefly Aerospace's SUV and Spaceflight's SHERPA.

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 ISAM ecosystem where the client spacecraft and ISAM servicing agents are co-designed to operate together and enable new missions and capabilities in the future.

Key to the ISAM ecosystem are standardized, interoperable interfaces for mechanical, fluid, power, data, and thermal connections between two spacecraft. Several providers have developed modular interfaces and servicing aids to perform ISAM 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. The interfaces between elements of the ISS enabled the modular assembly and servicing of the research platform. External payload platforms on the ISS (e.g., Express Logistics Carrier, JEM Exposed Facility, Bartolomeo) enable experiments and payloads to be robotically attached to and removed from the ISS to take advantage of the unique space environment. HST, which was built with the intent of servicing, was serviced five times by astronauts aboard the Space Shuttle. Other interfaces and modular spacecraft that have flown in space include Altius's mechanical interface, Dog Tag (which flies on OneWeb satellites), and Novawurks's SLEGO interface and modules, which can provide mechanical attachment and transfer data, power, and fluids between modules and payloads. The SLEGO architecture has been successfully tested in space through eXCITe, PODSat-1, and SIMPL, during which a modular spacecraft was assembled inside the ISS and deployed from the station.

These interfaces are designed for spacecraft of all sizes, 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.

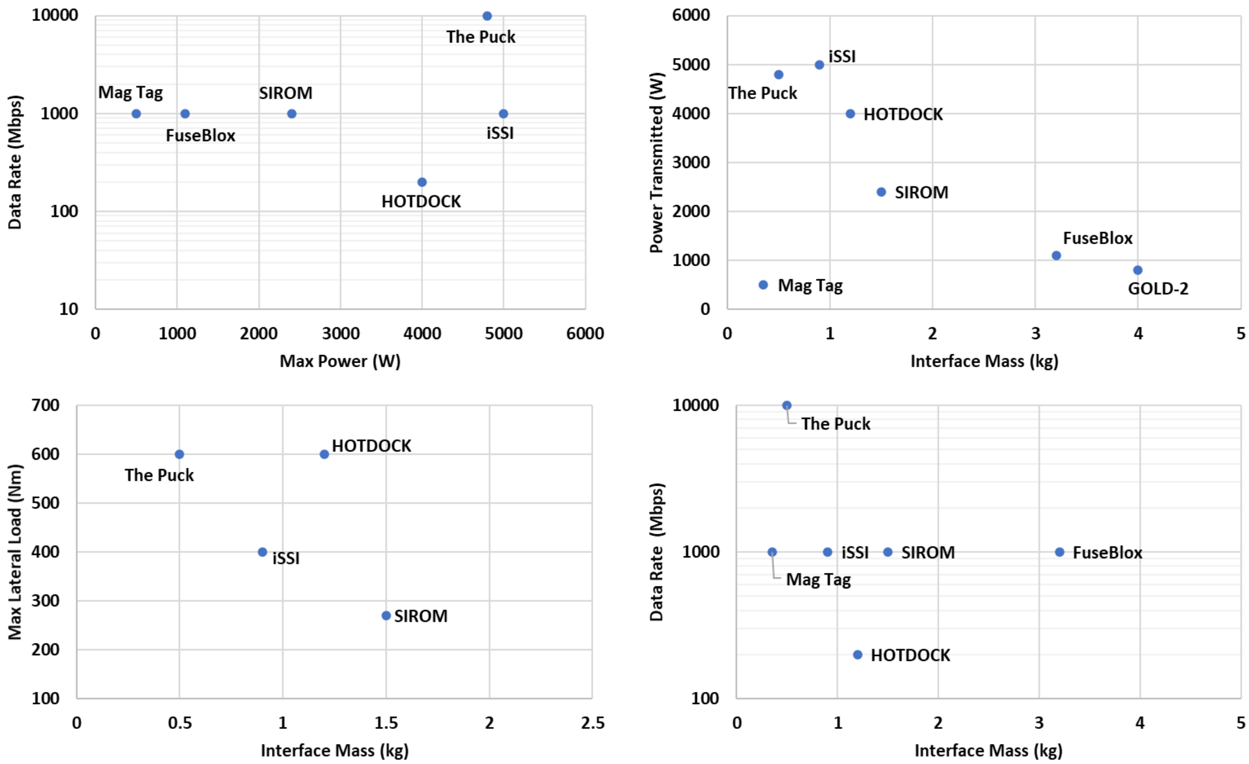

Figure 7: Modular interfaces are being developed to support multiple types of spacecraft to create an ISAM ecosystem where client satellites and ISAM servicing agents can readily create mechanical, fluid, power, data, and thermal connections. This figure presents some of the interfaces in use and under 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 ISAM 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 ISAM ecosystem relies on the servicing spacecraft and the client spacecraft to be co-designed to take advantage of ISAM capabilities, there are activities that are focused on servicing legacy spacecraft. While Landsat 7 was not intended to be serviced during its operational lifetime, NASA's OSAM-1 mission 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 spacecraft. For example, an MEP 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.

RRM-1 and -2 payloads on the ISS (2012-2015), using Dextre and custom robotic tooling, demonstrated the capability to interface to legacy spacecraft components not designed for in-space servicing for the purpose of engaging, manipulating, releasing, etc.

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 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. Technologies used for storable fluids are not necessarily extensible to complex, corrosive, or cryogenic fluids. A summary of the various activities that have been performed in refueling and fluid transfer are presented in Figure 8.

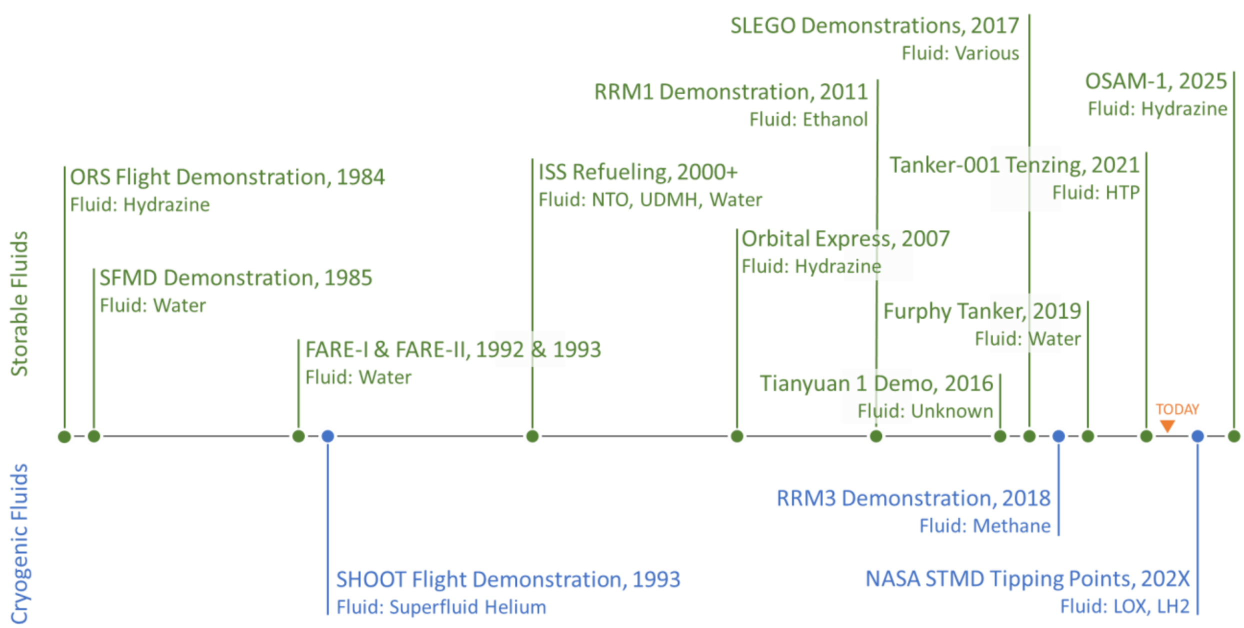

Figure 8: Storable fluid transfer has been demonstrated many times, including in operational missions like the ISS. The future is heading toward commercial refueling services (especially for storable fluids) and demonstrations are planned to test large-scale cryogenic fluid transfer in space.

Several storable fluid storage and transfer demonstrations occurred on various Space Shuttle missions (e.g., ORS, SFMD, FARE) in the 1980s and 1990s. Among other ISAM 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 the ISS with hydrazine, NTO, and water since 2000. RRM-1 on the ISS (2012) demonstrated the capability to interface to legacy spacecraft components and perform a fluid (ethanol) fill into a mock spacecraft fuel tank. In 2019, astronauts installed a new thermal management system onto the ISS-based Alpha Magnetic Spectrometer Instrument that provided a refill of CO_2 fluid.

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 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. In 2019, RRM-3 was able to prove cryogenic zero boil-off 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 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 and assemblies in space out of components delivered from Earth or produced in space. A major use case of this capability area is the 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 in-space 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 in-space 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. The EASE/ACCESS flight experiments 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 the 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. A number of welding experiments have also been conducted in space by astronauts. The first demonstration of welding in space was during the Vulkan experiment on the 1969 Soyuz-6 flight, which tested three methods of welding on a variety of metals.

Electron beam welding was further explored through a Skylab facility launched in 1973 to explore electron beam welding parameters, and during the Salyut-7 flight in 1984 which demonstrated the first use of a handheld electron beam welder.

In-space demonstrations of structural manufacturing and assembly are slated for demonstration on 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 Tethers Unlimited payload will manufacture a proof-of-concept 10-meter composite beam. The OSAM-2 mission will demonstrate the ability to 3D print two structural beams; one 10-meter beam that will deploy surrogate solar arrays and one 6-meter beam to demonstrate the ability to print multiple beams in one mission. The ESAMM subsystem of OSAM-2, developed by Redwire, will be responsible for additively manufacturing the extended structures.

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, Assemblers at NASA Langley in 2021, and ARMADAS at NASA Ames in 2021. These demonstrations are focused on the robotic and autonomous positioning and joining of standard structural elements. RRM-1, -2, -3 payloads demonstrated the capability to retrieve and stow tools to/from on-orbit protective enclosures (RRM payloads and the RiTS). In addition, the ORU/Tool Changeout Mechanisms was used to remove and install modular components (assemblies) to and from the RRM payloads to continue to demonstrate spacecraft servicing and assembly techniques. The RiTS capability for robotic tool stowage is an excellent flight-proven means of stowing tools and is adaptable to stow modular assembly components as an on-orbit structural and thermal protective enclosure of robotic access in future systems.

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 is the exploitation of previously launched, now defunct space assets which results in reduced strain on the space logistics supply chain. 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 the 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, reducing the power required to process materials, 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. With the ability to produce, inspect, and verify parts and goods at a consistent quality, 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, now a Redwire company, 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 operated on the ISS printed using plastic materials.

Current parts and goods manufacturing systems in development for demonstration on the ISS aim to add the ability to produce components from metal. Redwire has contributed in this area, including SIMPLE and the Multimaterial Fabrication Laboratory (both developed by Techshot, Inc., prior to acquisition by Redwire) and Vulcan (developed by Made In Space, prior to acquisition by Redwire). In addition to additive manufacturing capabilities, the Vulcan and the Multimaterial Fabrication Laboratory 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 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.

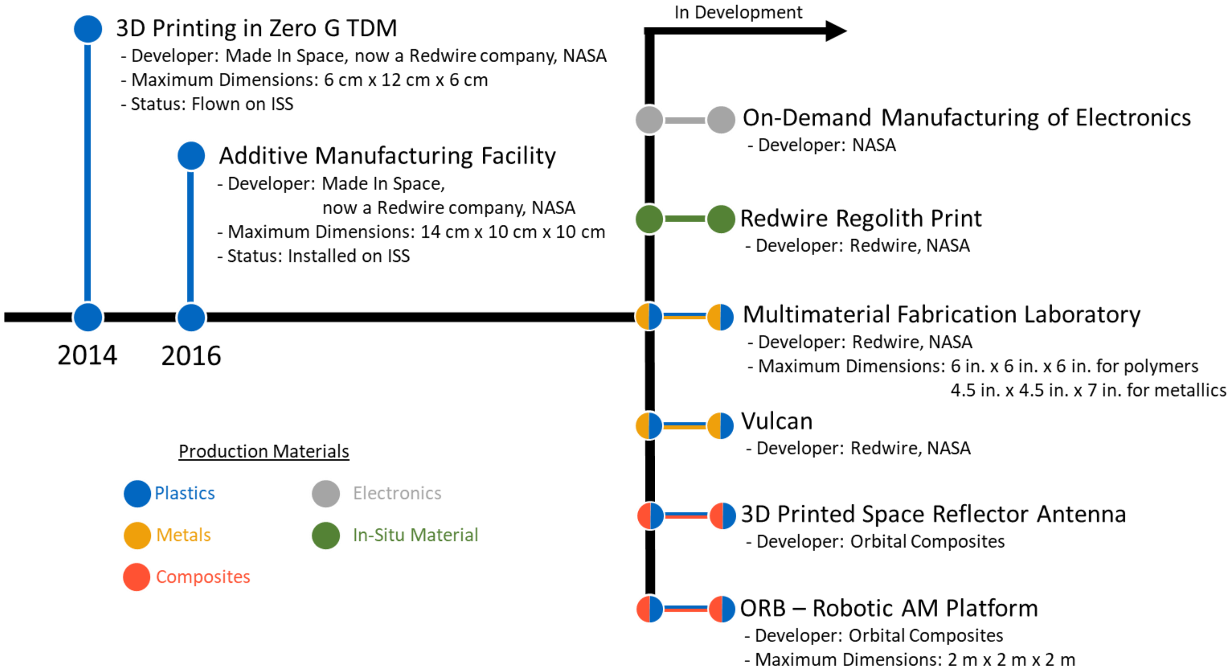

Figure 10: The first demonstrations of parts and goods manufacturing in space began in 2014 with the use of 3D printed plastics. Current production techniques in development aim to expand the production capabilities to metals, electronics, and even ISRU-regolith infused feedstock.

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 lunar or planetary surface structure, including horizontal (e.g., landing pads, roads) and vertical (e.g., power, habitation) construction. While initially the construction material must 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 remote and autonomous operations. 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.

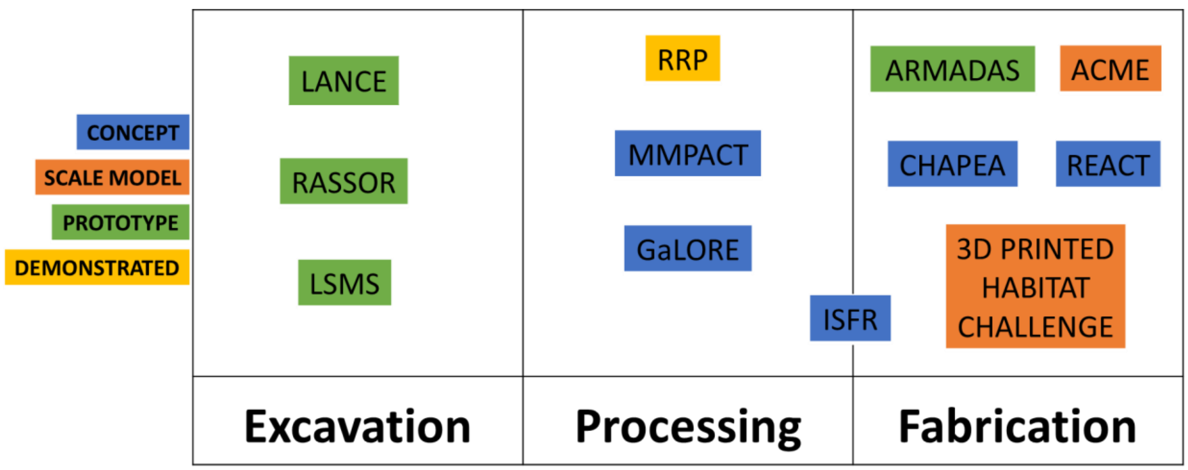

Figure 11: Surface Construction technologies, sorted into three main categories. Regolith excavation is the easiest category to simulate on Earth, reflected by it having the most advanced readiness level.

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 track and predict the position of orbital objects (space situational awareness) or assess the threat of 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 sensors, are also possible depending on the 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 RELL is a robotic tool used along with the SSRMS on ISS 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 in-space 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 AeroCube-10A and record images with an on-board camera during operation. The XSS family of satellites, produced by AFRL, 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.

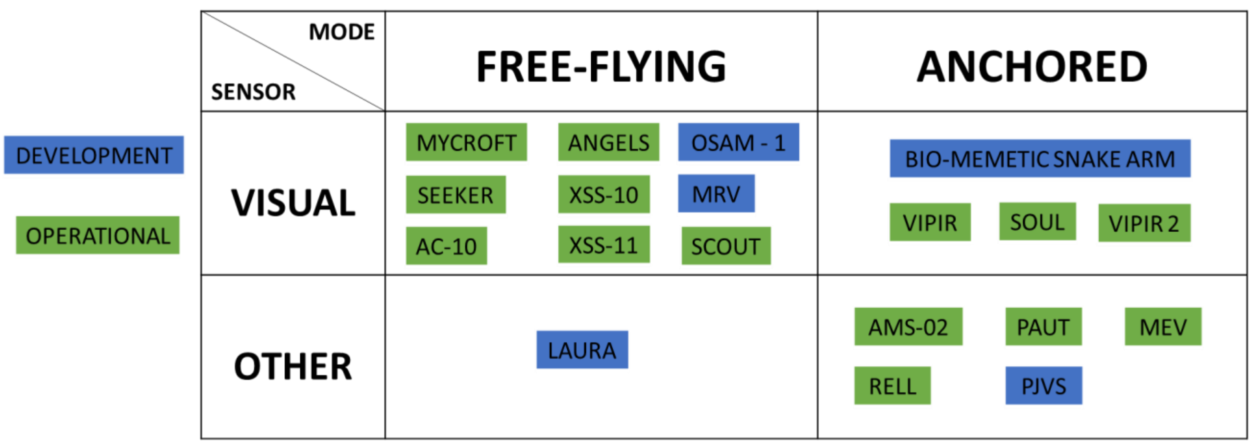

Figure 12: Inspection and metrology technologies, sorted into four main categories. Free-flying visual platforms command by far the highest in-demand application of this technology area.

4 ISAM FACILITIES

Facilities provide an important resource in advancing ISAM 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 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 for future ISAM development.

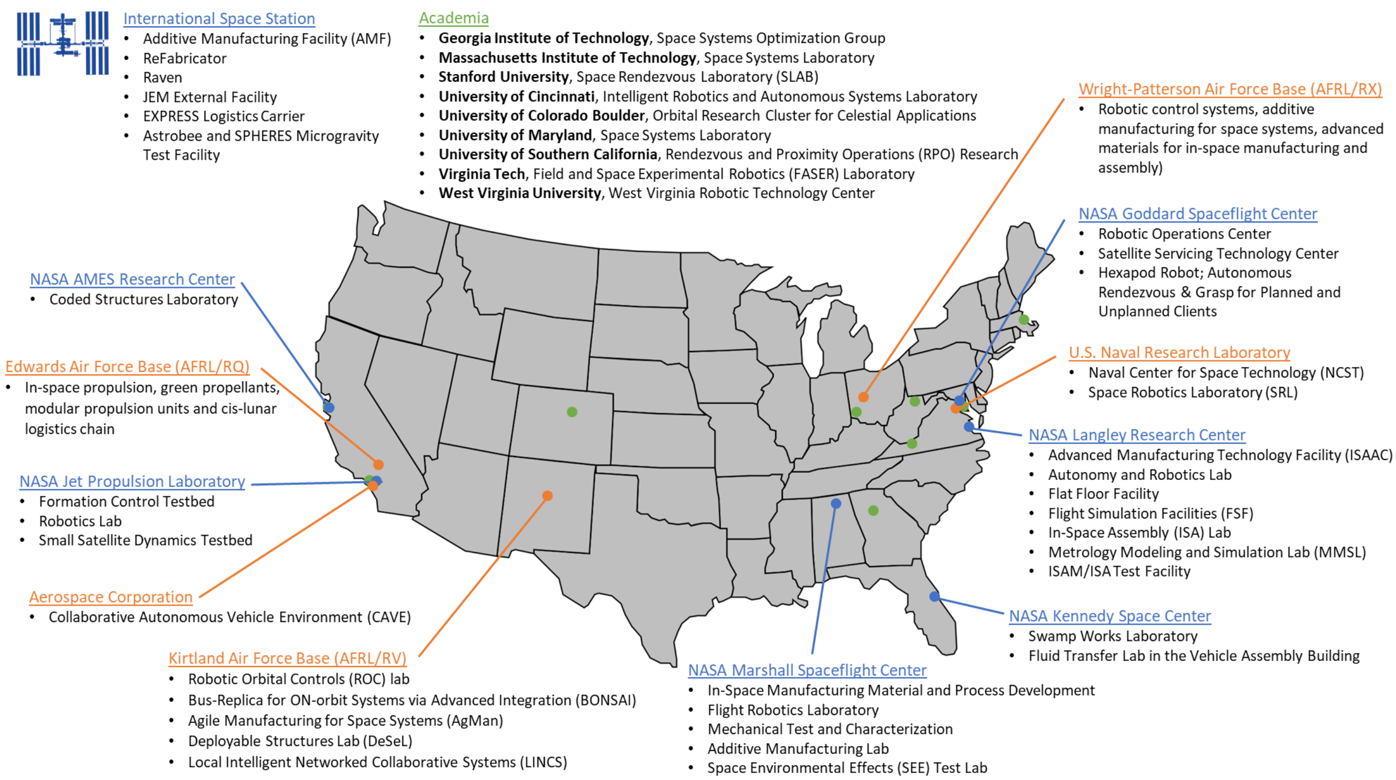

Figure 13: Facilities that have been advancing ISAM capabilities exist across the country and in space aboard the ISS. This figure presents a summary of several facilities, with Department of Defense and supporting FFRDC facilities in orange, NASA facilities in blue, and academic facilities in green.

5 CONTRIBUTORS

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6 APPENDIX

This appendix presents more details on the ISAM development activities and technologies that define the current state of ISAM.

Several of the ISAM activities and technologies contribute to larger missions, programs, or projects. Table 1 provides a breakdown of those larger missions into the entries that are captured in this appendix and provides the linkage to the capability area(s) that are applicable to that entry.

For the use of the tables found in this appendix, the capability areas are numbered from 1 to 11, as follows:

1. Robotic Manipulation
2. RPO, Capture, Docking, and Mating
3. Relocation
4. Planned Repair, Upgrade, Maintenance, and Installation
5. Unplanned or Legacy Repair and Maintenance
6. Refueling and Fluid Transfer
7. Structural Manufacturing and Assembly
8. Recycling, Reuse, and Repurposing
9. Parts and Goods Manufacturing
10. Surface Construction
11. Inspection and Metrology

Table 1: This table breaks down the larger missions into the entries in the appendix and identifies the applicable capability area(s).

Mission	Activity	Area
ARMADAS	Androgynous Fasteners [ARMADAS]	7
	ARMADAS	7, 10
	Mobile Metamaterial Internal Co-Integrator (MMIC-I) [ARMADAS]	1
	Scaling Omnidirectional Lattice Locomoting Explorer (SOLL-E) [ARMADAS]	1
ETS-VII	Engineering Test Satellite VII (ETS-VII)	1, 2
HST	Servicing Mission 1 (STS-61) [HST]	2, 3, 4
	Servicing Mission 2 (STS-82) [HST]	2, 3, 4, 5
	Servicing Mission 3A (STS-103) [HST]	2, 4
	Servicing Mission 3B (STS-109) [HST]	2, 3, 4
	Servicing Mission 4 (STS-125) [HST]	2, 4, 5
ISM	3D Printing in Zero G TDM [ISM]	9

Mission	Activity	Area
	Additive Manufacturing Facility (AMF) [ISM]	9
	Metal Advanced Manufacturing Bot-Assisted Assembly (MAMBA)	8
	Multimaterial Fabrication Laboratory [ISM]	9
	On-Demand Manufacturing of Electronics (ODME) [ISM]	9
	Recyclable Packaging Materials	8
ISM	Redwire Regolith Print (RegISS) [ISM]	9, 10
	ReFabricator [ISS]	8
	Sintered Inductive Metal Printer with Laser Exposure (SIMPLE) [ISM]	9
	Vulcan [ISM]	9
ISS	Alpha Magnetic Spectrometer (AMS-02) [ISS]	11
	Bio-memetic Snake Arm Robot [ISS]	11
	Canadarm2 (Space Station Remote Manipulator System) [ISS]	1
	CAS [ISS]	7
	Dextre [ISS]	1
	European Robotic Arm (ERA) [ISS]	1
	Furphy Prototype Tanker [ISS]	6
	GOLD-2 Connector [ISS]	4
	International Berthing and Docking Mechanism (IBDM) [ISS]	2
	International Space Station Truss/Backbone [ISS]	7
	ISS Reboost	3
	Japanese Experiment Module Remote Manipulator System (JEM-RMS) [ISS]	1
	Japanese Experiment Module Small Fine Arm [ISS]	1
	KRAKEN [ISS]	1
	MRTAS [ISS]	7
	NASA Docking System (NDS)[ISS]	2
	PMA [ISS]	2
	Progress Vehicle and ATV Refueling of ISS [ISS]	6
	RAVEN [ISS]	2
	Robonaut2 [ISS]	1
	Robotic External Leak Locator (RELL) [ISS]	11
	RTAS [ISS]	7
	Seeker [ISS]	11
	Sonatest Veo PAUT [ISS]	11
	SSAS [ISS]	7
	Strela Cargo Cranes [ISS]	1
MEV	Mission Extension Vehicle (MEV)	2, 3, 11
Orbital Express	Orbital Express	2, 4, 6, 11
	Orbital Express Demonstration Manipulator System (OEDMS) [Orbital Express]	1

Mission	Activity	Area
OSAM-1	MakerSat	7
	NASA Servicing Arm [OSAM-1]	1
	OSAM-1	2, 5, 6, 11
	Robotically Compatible Erectable Joint with Square Cross-Section [OSAM-1]	7
OSAM-1	Space Infrastructure Dexterous Robot (SPIDER) [OSAM-1]	1, 7
OSAM-2	ESAMM	7
	Manufacturing Health Monitoring System (MHMS) [OSAM-2]	11
	OSAM-2	7
	xLink Robotic Arm [OSAM-2]	1, 7
RRM	Cryogenic Servicing Tool (CST) [RRM]	6
	Multifunction Tool [RRM]	6
	Multi-Function Tool 2 (MFT2) [RRM]	6
	Nozzle Tool [RRM]	6
	Robotic Refueling Mission 1 (RRM1)	6
	Robotic Refueling Mission 2 (RRM2)	5
	Robotic Refueling Mission 3 (RRM3)	6
	Safety Cap Tool [RRM]	6
	Visual Inspection Poseable Invertebrate Robot (VIPIR) [RRM]	11
	Wire Cutter Tool [RRM]	5
RSGS	Front-end Robotic Enabling Near-term Demonstration (FREND) [RSGS]	1
	Mission Robotic Vehicle (MRV) [RSGS]	2, 3, 5, 11

Table 2 presents all the entries listed in the *ISAM State of Play* and highlights applicable capability area(s). 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. For the detailed entries, the "Status" and "First Use Date" information have specific lexicons. These definitions are listed below for "Status":

- In Development: ongoing development project
- Operational: ongoing flight project or mission
- Concluded: project ended or was canceled
- Completed: project had an operational flight or similar and has been completed

The definitions for "First Use Date" are listed below:

- N/A: canceled without technology use
- Unavailable: unable to find the use date
- TBD: project in development without scheduled future mission
- Scheduled for 20XX: scheduled future mission

Table 2: This table lists all the ISAM development activities and technologies in the ISAM State of Play mapped to the applicable capability area(s). The text in the columns of this table are unique identifiers for each entry detailed in the appendix.

Activity	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**
3D Printed Habitat Challenge										SC01	
3D Printed Space Reflector Antenna									PGM01		
3D Printing in Zero G TDM [ISM]									PGM02		
Additive Construction with Mobile Emplacement (ACME)										SC02	
Additive Manufacturing Facility (AMF) [ISM]									PGM03		
AeroCube-10		RCDM01									
AeroCube-10 (AC-10)											IM01
Alpha Magnetic Spectrometer (AMS-02) [ISS]											IM02
Androgynous Fasteners [ARMADAS]							SMA01				
ANGELS		RCDM02									IM03
Aolong-1		RCDM03	R01								
APAS [ISS]		RCDM04									
Argon Autonomous Rendezvous and Docking (AR&D) Sensor		RCDM05									
ARMADAS							SMA02			SC03	
Assemblers	RM01						SMA03				
ASTP-DM		RCDM06									
Axon/Dactylus				PRUMI01							
Bio-memetic Snake Arm Robot [ISS]											IM04
Canadarm (Shuttle Remote Manipulator System)	RM02										
Canadarm2 (Space Station Remote Manipulator System) [ISS]	RM03										
Canadarm3	RM04										
CAS [ISS]							SMA04				
CHAPEA										SC04	
Cryogenic Servicing Tool (CST) [RRM]						RFT01					
Dextre [ISS]	RM05										
Dog Tag				PRUMI02							
EASE/ACCESS							SMA05				

Activity	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**
End-of-Life Services by Astroscale Demonstration (ELSA-d)		RCDM07	R02								
Engineering Test Satellite VII (ETS-VII)	RM06	RCDM08									
ESAMM							SMA06				
European Robotic Arm (ERA) [ISS]	RM07										
Fluid Acquisition & Resupply Experiment I (FARE-I)						RFT02					
Fluid Acquisition & Resupply Experiment II (FARE-II)						RFT03					
Front-end Robotic Enabling Near-term Demonstration (FREND) [RSGS]	RM08										
Furphy Prototype Tanker [ISS]						RFT04					
FuseBlox				PRUMI03							
GaLORE Project										SC05	
GOLD-2 Connector [ISS]				PRUMI04							
Hinge for Use in a Tension Stiffened and Tendon Actuated Manipulator							SMA07				
HOTDOCK				PRUMI05							
iBOSS iSSI				PRUMI06							
In Situ Construction GCD Project										SC06	
In-Situ Fabrication and Repair Project (ISFR)										SC07	
Instrument Deployment Arm (Insight)	RM09										
International Berthing and Docking Mechanism (IBDM) [ISS]		RCDM09									
International Space Station Truss/Backbone [ISS]							SMA08				
Ion			R03								
ISS Reboost			R04								
Japanese Experiment Module Remote Manipulator System (JEM-RMS) [ISS]	RM10										
Japanese Experiment Module Small Fine Arm [ISS]	RM11										
Joint Design Using Electron Beam Welding for							SMA09				

Activity	1	2	3	4	5	6	7	8	9	10	11
Autonomous In-Space Truss Assembly (EBW Joint)											
KRAKEN [ISS]	RM12										
LANCE										SC08	
Laura											IM05
LEO Knight		RCDM10			ULRM01						
Lightweight Surface Manipulator System (LSMS)	RM13									SC09	
Mag Tag				PRUMI07							
MakerSat							SMA10				
Manufacturing Health Monitoring System (MHMS) [OSAM-2]											IM06
Mars Exploration Rover Robotic Arm	RM14										
Mars Science Laboratory Robotic Arm	RM15										
Mars Surveyor 2001 Robotic Arm	RM16										
Mars Volatiles and Climate Surveyor Robotic Arm (MVACS)	RM17										
Metal Advanced Manufacturing Bot-Assisted Assembly (MAMBA)								RRR01			
Mission Extension Pods			R05		ULRM02						
Mission Extension Vehicle (MEV)		RCDM11	R06								IM07
Mission Robotic Vehicle (MRV) [RSGS]		RCDM12	R07		ULRM03						IM08
MMPACT										SC10	
Mobile Metamaterial Internal Co-Integrator (MMIC-I) [ARMADAS]	RM18										
MRTAS [ISS]							SMA11				
Multifunction Tool [RRM]						RFT06					
Multi-Function Tool 2 (MFT2) [RRM]						RFT05					
Multimaterial Fabrication Laboratory [ISM]									PGM04		
Mycroft		RCDM13									IM09
NASA Docking System (NDS)[ISS]		RCDM14									
NASA Intelligent Jigging and Assembly Robot (NINJAR)							SMA12				

Activity	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**
NASA Servicing Arm [OSAM-1]	RM19										
NASA STMD 2020 Tipping Point Selections on Cryogenic Fluid Management Technology Demonstration						RFT07					
Nozzle Tool [RRM]						RFT08					
On-Demand Manufacturing of Electronics (ODME) [ISM]									PGM05		
ORB - Robotic AM Platform									PGM06		
Orbital Express		RCDM15		PRUMI08		RFT09					IM10
Orbital Express Demonstration Manipulator System (OEDMS) [Orbital Express]	RM20										
Orbital Maneuvering Vehicle (OMV)			R08								
Orbital Refueling System (ORS) Flight Demonstration						RFT10					
Orbiter			R09								
OSAM-1		RCDM16			ULRM04	RFT11					IM11
OSAM-2							SMA13				
Otter		RCDM17	R10								
Perseverance Sample Handling Assembly (SHA)	RM21										
Phoenix Mars Lander Robotic Arm	RM22										
PMA [ISS]		RCDM18									
Precision Assembled Space Structures (PASS)							SMA14				
Programmable Josephson Voltage Standard (PJVS)											IM12
Progress Vehicle and ATV Refueling of ISS [ISS]						RFT12					
Ranger	RM23										
RASSOR										SC11	
RAVEN [ISS]		RCDM19									
REACT										SC12	
Recyclable Packaging Materials								RRR02			
Redwire Regolith Print (RegISS) [ISM]									PGM07	SC013	
ReFabricator [ISS]								RRR03			
Robonaut2 [ISS]	RM24										

Activity	1	2	3	4	5	6	7	8	9	10	11
Robotic External Leak Locator (RELL) [ISS]											IM13
Robotic Refueling Mission 1 (RRM1)						RFT13					
Robotic Refueling Mission 2 (RRM2)					ULRM05						
Robotic Refueling Mission 3 (RRM3)						RFT14					
Robotically Compatible Erectable Joint with Square Cross-Section [OSAM-1]							SMA15				
RTAS [ISS]							SMA16				
Safety Cap Tool [RRM]						RFT15					
Salyut-7 Welding Experiment							SMA17				
Scaling Omnidirectional Lattice Locomoting Explorer (SOLL-E) [ARMADAS]	RM25										
SCOUT		RCDM20									IM14
Seeker [ISS]											IM15
Servicing Mission 1 (STS-61) [HST]		RCDM21	R11	PRUMI09							
Servicing Mission 2 (STS-82) [HST]		RCDM22	R12	PRUMI10	ULRM06						
Servicing Mission 3A (STS-103) [HST]		RCDM23		PRUMI11							
Servicing Mission 3B (STS-109) [HST]		RCDM24	R13	PRUMI12							
Servicing Mission 4 (STS-125) [HST]		RCDM25		PRUMI13	ULRM07						
SHEAth-based Rollable Lenticular-Shaped and Low-Stiction (SHEARLESS) Composite Booms							SMA18				
SHERPA			R14								
Shijian-17		RCDM26									
Sintered Inductive Metal Printer with Laser Exposure (SIMPLE) [ISM]									PGM08		
Skylab Materials Processing Facility Experiments							SMA19				
SLEGO Architecture				PRUMI14		RFT16	SMA20				
Sonatest Veo PAUT [ISS]											IM16
SOUL		RCDM27		PRUMI15							IM17
Space Infrastructure Dexterous Robot (SPIDER) [OSAM-1]	RM26						SMA21				

Activity	1	2	3	4	5	6	7	8	9	10	11
Space Utility Vehicle (SUV)			R15								
SSAS [ISS]							SMA22				
SSVP		RCDM28									
Standard Interface for Robotic Manipulation of Payloads in Future Space Missions (SIROM)				PRUMI16							
Storage Fluid Management Demonstration (SFMD)						RFT17					
Strela Cargo Cranes [ISS]	RM27										
Structural Joint With Multi-Axis Load Carrying Capability							SMA23				
Strut Attachment, Manipulation, and Utility Robotic Aide (SAMURAI)							SMA24				
Superfluid Helium On-Orbit Transfer (SHOOT) Flight Demonstration						RFT18					
Tailored Universal Feedstock for Forming (TuFF) Reformability Demo								RRR04			
TALISMAN	RM28										
Tanker-001 Tenzing		RCDM29				RFT19					
The Puck & Service Pods				PRUMI17							
Thermally Reversible Polymers for AM Feedstock								RRR05			
Tianyuan 1 refueling demonstration						RFT20					
Vigoride			R16								
Visual Inspection Poseable Invertebrate Robot (VIPIR) [RRM]											IM18
Visual Inspection Poseable Invertebrate Robot 2 (VIPIR2) [RRM]											IM19
Vulcan [ISM]									PGM09		
Vulkan Experiment							SMA25				
Wire Cutter Tool [RRM]					ULRM08						
xLink Robotic Arm [OSAM-2]	RM29						SMA26				
XSS-10		RCDM30									IM20
XSS-11		RCDM31									IM21

6.1 Robotic Manipulation

6.1.1 RM01: 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:** United States

First Use Date: TBD **Status:** In Development

Reach (m): 1.01

Degrees of Freedom: Unavailable

Grapple Type: Unavailable

6.1.2 RM02: 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:** Completed

Reach (m): 15

Degrees of Freedom: 8

Grapple Type: Snare End Effector

6.1.3 RM03: Canadarm2 (Space Station Remote Manipulator System) [ISS]

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:** Operational

Reach (m): 17.6

Degrees of Freedom: 7

Grapple Type: Snare End Effector, Latches, Umbilicals

6.1.4 RM04: 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: Scheduled for 2024
Status: In Development
Reach (m): 8.5
Degrees of Freedom: 7
Grapple Type: Unavailable

6.1.5 RM05: Dextre [ISS]

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

6.1.6 RM06: Engineering Test Satellite VII (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: NASDA (now JAXA)
Country: Japan
First Use Date: 1998
Status: Completed
Reach (m): 2
Degrees of Freedom: 6
Grapple Type: Grapple

6.1.7 RM07: European Robotic Arm (ERA) [ISS]

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:** EU

First Use Date: 2021 **Status:** Operational

Reach (m): 11.3

Degrees of Freedom: 7

Grapple Type: Grapple, Integrated Tools

6.1.8 RM08: Front-end Robotic Enabling Near-term Demonstration (FREND) [RSGS]

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:** United States

First Use Date: 2007 **Status:** Completed

Reach (m): 1.8

Degrees of Freedom: 7

Grapple Type: Grapple

6.1.9 RM09: 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:** United States

First Use Date: 2018 **Status:** Operational

Reach (m): 1.9

Degrees of Freedom: 4

Grapple Type: Scoop, Grapple, Camera

6.1.10 RM10: Japanese Experiment Module Remote Manipulator System (JEM-RMS) [ISS]

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:** Operational

Reach (m): 10

Degrees of Freedom: 6

Grapple Type: Grapple, JEM SFA Connection

6.1.11 RM11: Japanese Experiment Module Small Fine Arm [ISS]

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:** Operational

Reach (m): 2.2

Degrees of Freedom: 6

Grapple Type: 3 Fingers, Torque Driver, Electric Connectors

6.1.12 RM12: KRAKEN [ISS]

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:** United States

First Use Date: TBD **Status:** In Development

Reach (m): 1

Degrees of Freedom: 7

Grapple Type: Swappable, Tool-Change Interface, Power/Data Interface

6.1.13 RM13: 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:** United States

First Use Date: TBD **Status:** In Development

Reach (m): 7.5

Degrees of Freedom: 3

Grapple Type: Unavailable

6.1.14 RM14: Mars Exploration Rover Robotic Arm

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:** United States

First Use Date: 2004 **Status:** Completed

Reach (m): 1

Degrees of Freedom: 5

Grapple Type: Abrasion Tool, Spectrometer, Camera

6.1.15 RM15: 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:** United States

First Use Date: 2012 **Status:** Operational

Reach (m): 2.2

Degrees of Freedom: 5

Grapple Type: 5 Scientific Instruments, Drill

6.1.16 RM16: 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:** United States

First Use Date: 2001 **Status:** Concluded

Reach (m): 2

Degrees of Freedom: 4

Grapple Type: Scoop, Scraping Blades, Electrometer

6.1.17 RM17: Mars Volatiles and Climate Surveyor Robotic Arm (MVACS)

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

Developer: NASA/Univ of Ariz **Country:** United States

First Use Date: 1999 **Status:** Concluded

Reach (m): 2.2

Degrees of Freedom: 4

Grapple Type: Scoop, Temp probe, Camera

6.1.18 RM18: Mobile Metamaterial Internal Co-Integrator (MMIC-I) [ARMADAS]

Description: ARMADAS Integration Robot - used for internal climbing and completing inter-voxel connection through bolting.

Developer: NASA Ames **Country:** United States

First Use Date: TBD **Status:** In Development

Reach (m): 0.3

Degrees of Freedom: 5 locomotion +16 end effector

Grapple Type: Internal framework gripping interface

6.1.19 RM19: NASA Servicing Arm [OSAM-1]

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. In particular, 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:** United States

First Use Date: Scheduled for 2025 **Status:** In Development

Reach (m): 2.46

Degrees of Freedom: 7

Grapple Type: Six-Axis Force/Torque Sensor

6.1.20 RM20: Orbital Express Demonstration Manipulator System (OEDMS) [Orbital Express]

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:** United States

First Use Date: 2007 **Status:** Completed

Reach (m): 2.8

Degrees of Freedom: 6

Grapple Type: Mouse Trap, Cone, Probe

6.1.21 RM21: 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 wrist "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:** United States

First Use Date: 2020 **Status:** Operational

Reach (m): 2.1

Degrees of Freedom: 5

Grapple Type: Tool Turret, SHERLOC, WATSON, PIXL, GDRT, Drill

6.1.22 RM22: 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:** United States

First Use Date: 2008 **Status:** Completed

Reach (m): 2

Degrees of Freedom: 4

Grapple Type: Scoop, Camera

6.1.23 RM23: Ranger

Description: Ranger, a four-armed repair robot, is currently under testing in the Maryland Space Systems Laboratory. This robot was proposed for Hubble Servicing Missions but was eventually defunded by NASA. First use of robot control of "hazardous" payload, leveraged by Robonaut and Restore.

Developer: UMD Space Systems Laboratory
Country: United States
First Use Date: 1995
Status: In Development
Reach (m): 1.35
Degrees of Freedom: 8
Grapple Type: Bolt & Angle Drives, Jaw gripper

6.1.24 RM24: Robonaut2 [ISS]

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: United States
First Use Date: 1999
Status: Operational
Reach (m): 0.812
Degrees of Freedom: 42
Grapple Type: 12-DOF Hands

6.1.25 RM25: Scaling Omnidirectional Lattice Locomoting Explorer (SOLL-E) [ARMADAS]

Description: ARMADAS Cargo Robot - used for material transport and placement through an inchworming process on external structure.

Developer: NASA Ames
Country: United States
First Use Date: TBD
Status: In Development
Reach (m): 0.7
Degrees of Freedom: 5 locomotion + 8 end effector
Grapple Type: External framework gripping interface

6.1.26 RM26: Space Infrastructure Dexterous Robot (SPIDER) [OSAM-1]

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: United States
First Use Date: Scheduled for 2025
Status: In Development
Reach (m): 5
Degrees of Freedom: 7
Grapple Type: MDA Provided dexterous end effector

6.1.27 RM27: Strela Cargo Cranes [ISS]

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:** Operational

Reach (m): 14

Degrees of Freedom: Unavailable

Grapple Type: Unavailable

6.1.28 RM28: 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:** United States

First Use Date: TBD **Status:** In Development

Reach (m): 20

Degrees of Freedom: 5

Grapple Type: swappable end effector

6.1.29 RM29: xLink Robotic Arm [OSAM-2]

Description: The Motiv xLink robotic arm will be used during NASA's OSAM-2 mission to position 3D printed solar array elements, connect deployable solar arrays, and position the onboard 3D printer.

Developer: Motiv **Country:** United States

First Use Date: Scheduled for 2024 **Status:** In Development

Reach (m): 1-3

Degrees of Freedom: 4-7

Grapple Type: Unavailable

6.2 RPO, Capture, Docking, and Mating

6.2.1 RCDM01: 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:** Completed

Contact vs. Non-Contact: Non-Contact

Misalignment Tolerance: N/A

Max RPO Initiation Distance (m): Unavailable

Cooperative vs. Non-Cooperative: Unavailable

6.2.2 RCDM02: 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:** Completed

Contact vs. Non-Contact: Non-Contact

Misalignment Tolerance: N/A

Max RPO Initiation Distance (m): 50000

Cooperative vs. Non-Cooperative: Non-cooperative

6.2.3 RCDM03: Aolong-1

Description: Aolong-1 is a Chinese developed satellite which demonstrated the removal of a simulated space debris object from orbit. The satellite captured the space debris and altered the trajectory to de-orbit in Earth's atmosphere.

Developer: NUDT/PLA **Country:** China

First Use Date: 2016 **Status:** Unavailable

Contact vs. Non-Contact: Contact

Misalignment Tolerance: Unavailable

Max RPO Initiation Distance (m): Unavailable

Cooperative vs. Non-Cooperative: Non-cooperative

6.2.4 RCDM04: APAS [ISS]

Description: Androgynous Peripheral Attachment System is an androgynous docking mechanism used on the ISS. The system was first used on the ISS between US Pressurized Mating Adapter 1 and the Russian FGB.

Developer: RKK Energiya **Country:** United States, USSR

First Use Date: 1975 **Status:** Operational

Contact vs. Non-Contact: Contact

Misalignment Tolerance: Unavailable

Max RPO Initiation Distance (m): Unavailable

Cooperative vs. Non-Cooperative: Both

6.2.5 RCDM05: 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:** United States

First Use Date: 2012 **Status:** Completed

Contact vs. Non-Contact: Non-Contact

Misalignment Tolerance: N/A

Max RPO Initiation Distance (m): 90

Cooperative vs. Non-Cooperative: Non-cooperative

6.2.6 RCDM06: ASTP-DM

Description: The Apollo-Soyuz Test Project Docking Module was a modification made to the Apollo Command and Service Module to allow for mating with the Soyuz spacecraft. The module was designed jointly by the USA and USSR and was constructed in the US.

Developer: North American Rockwell **Country:** United States, USSR

First Use Date: 1975 **Status:** Completed

Contact vs. Non-Contact: Contact

Misalignment Tolerance: Unavailable

Max RPO Initiation Distance (m): Unavailable

Cooperative vs. Non-Cooperative: Unavailable

6.2.7 RCDM07: 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: 2021 **Status:** Operational
Contact vs. Non-Contact: Contact
Misalignment Tolerance: Unavailable
Max RPO Initiation Distance (m): Unavailable
Cooperative vs. Non-Cooperative: Both

6.2.8 RCDM08: Engineering Test Satellite VII (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:** United States
First Use Date: 1998 **Status:** Completed
Contact vs. Non-Contact: Contact
Misalignment Tolerance: 1.3mm arm tolerance
Max RPO Initiation Distance (m): 10000
Cooperative vs. Non-Cooperative: Cooperative

6.2.9 RCDM09: International Berthing and Docking Mechanism (IBDM) [ISS]

Description: International Berthing & Docking Mechanism, composed of the soft docking system and the hard docking system. The system is contact force sensing, magnetically latched for capture, low impact, and capable of docking and berthing large and small vehicles.

Developer: ESA, QinetiQ Space, Sierra Nevada Corp., SENER, RAUG, Maxon
Country: ESA
First Use Date: TBD
Status: In Development
Contact vs. Non-Contact: Contact
Misalignment Tolerance: Unavailable
Max RPO Initiation Distance (m): Unavailable
Cooperative vs. Non-Cooperative: Both

6.2.10 RCDM10: 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: In Development
Contact vs. Non-Contact: Contact
Misalignment Tolerance: Unavailable
Max RPO Initiation Distance (m): Unavailable
Cooperative vs. Non-Cooperative: Cooperative

6.2.11 RCDM11: Mission Extension Vehicle (MEV)

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: 2020
Status: Operational
Contact vs. Non-Contact: Contact
Misalignment Tolerance: Unavailable
Max RPO Initiation Distance (m): 80
Cooperative vs. Non-Cooperative: Cooperative

6.2.12 RCDM12: Mission Robotic Vehicle (MRV) [RSGS]

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: In Development
Contact vs. Non-Contact: Contact
Misalignment Tolerance: Unavailable
Max RPO Initiation Distance (m): Unavailable
Cooperative vs. Non-Cooperative: Both

6.2.13 RCDM13: 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: Operational
Contact vs. Non-Contact: Non-Contact
Misalignment Tolerance: N/A
Max RPO Initiation Distance (m): 3500
Cooperative vs. Non-Cooperative: Unavailable

6.2.14 RCDM14: NASA Docking System (NDS)[ISS]

Description: The NASA Docking System is an androgynous docking system installed on the ISS which meets the International Docking System Standard. This docking system allows for vehicles such as the Orion, Dragon, or Starliner spacecraft to visit the ISS.

Developer: NASA
Country: United States
First Use Date: 2018
Status: Operational
Contact vs. Non-Contact: Contact
Misalignment Tolerance: 0.1 m, 5 degrees in one axis
Max RPO Initiation Distance (m): Unavailable
Cooperative vs. Non-Cooperative: Cooperative

6.2.15 RCDM15: 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: Completed
Contact vs. Non-Contact: Contact
Misalignment Tolerance: 5 degrees +/-
Max RPO Initiation Distance (m): 1000000
Cooperative vs. Non-Cooperative: Cooperative

6.2.16 RCDM16: 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: Scheduled for 2025
Status: In Development
Contact vs. Non-Contact: Contact
Misalignment Tolerance: Unavailable
Max RPO Initiation Distance (m): Unavailable
Cooperative vs. Non-Cooperative: Non-cooperative

6.2.17 RCDM17: Otter

Description: Otter, from Starfish Space, is a low cost, rapidly deployable ~ 200 kg space tug which will perform life extension missions in GEO and end-of-life satellite removal missions in LEO. Otter will leverage Starfish Space's CEPHALOPOD guidance and control software, to demonstrate rendezvous and proximity operations using both chemical and electric propulsion on the Tenzing satellite, which is currently on orbit. Other key components of the Otter space tug include CETACEAN, a relative navigation software, and Nautilus, a capture mechanism capable of docking without standardized, pre-installed interfaces on client satellites.

Developer: Starfish Space
Country: United States
First Use Date: TBD
Status: In Development
Contact vs. Non-Contact: Contact
Misalignment Tolerance: Unavailable
Max RPO Initiation Distance (m): Unavailable
Cooperative vs. Non-Cooperative: Unavailable

6.2.18 RCDM18: PMA [ISS]

Description: Pressurized Mating Adapters convert common berthing mechanisms on the ISS to APAS-95 docking ports. These are comprised of a passive common berthing mechanism port and a passive APAS port.

Developer: Boeing
Country: United States
First Use Date: 1998
Status: Operational
Contact vs. Non-Contact: Contact
Misalignment Tolerance: Unavailable
Max RPO Initiation Distance (m): Unavailable
Cooperative vs. Non-Cooperative: Non-cooperative

6.2.19 RCDM19: RAVEN [ISS]

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: United States
First Use Date: 2017
Status: Operational
Contact vs. Non-Contact: Non-Contact
Misalignment Tolerance: N/A
Max RPO Initiation Distance (m): 100
Cooperative vs. Non-Cooperative: Both

6.2.20 RCDM20: SCOUT

Description: SCOUT helps SpaceCraft Observe and Understand Things around them. Enables on-demand, on-site inspections for space assets. SCOUT-Sat constellation enables sustainable access to anything in GEO within 6 hours, essentially serving as 24-hour security cameras.

Developer: Scout
Country: United States
First Use Date: Scheduled for 2023
Status: In Development
Contact vs. Non-Contact: Non-Contact
Misalignment Tolerance: N/A
Max RPO Initiation Distance (m): Unavailable
Cooperative vs. Non-Cooperative: Both

6.2.21 RCDM21: Servicing Mission 1 (STS-61) [HST]

Description: STS-61 was the first planned servicing mission of the HST. During this mission, new instruments were installed, and the primary mirror was corrected. In addition, the shuttle boosted the orbit of HST during this mission.

Developer: NASA
Country: United States
First Use Date: 1993
Status: Completed
Contact vs. Non-Contact: Contact
Misalignment Tolerance: Unavailable
Max RPO Initiation Distance (m): Unavailable
Cooperative vs. Non-Cooperative: Cooperative

6.2.22 RCDM22: Servicing Mission 2 (STS-82) [HST]

Description: STS-82 was the second planned servicing mission to the HST. During this mission, the shuttle crew swapped the Space Telescope Imaging Spectrograph (STIS), the Near Infrared Camera and Multi-Object Spectrometer (NICMOS), and the Fine Guidance Sensor 1 (FGS1) for outdated instruments, the Goddard High Resolution Spectrograph, the Faint Object Spectrograph, and the FGS, respectively. In addition, the Solid State Recorder (SSR) replaced the HST reel-to-reel recorders and one of the four Reaction Wheel Assemblies (RWA) was replaced with a refurbished spare. The shuttle also boosted HST during this mission.

Developer: NASA **Country:** United States
First Use Date: 1997 **Status:** Completed
Contact vs. Non-Contact: Contact
Misalignment Tolerance: Unavailable
Max RPO Initiation Distance (m): Unavailable
Cooperative vs. Non-Cooperative: Cooperative

6.2.23 RCDM23: Servicing Mission 3A (STS-103) [HST]

Description: STS-103 was the third servicing mission of the HST. During this mission, astronauts replaced 4 failed and 2 working RWAs with new models; Installed a new FGS, VIK, spare SSR, and SSAT; and replaced HST's computer, NOBL, and SSRF. New thermal insulation blankets were also installed.

Developer: NASA **Country:** United States
First Use Date: 1999 **Status:** Completed
Contact vs. Non-Contact: Contact
Misalignment Tolerance: Unavailable
Max RPO Initiation Distance (m): Unavailable
Cooperative vs. Non-Cooperative: Cooperative

6.2.24 RCDM24: Servicing Mission 3B (STS-109) [HST]

Description: During STS-109, the fourth servicing mission to HST, a new instrument, the FOC, replaced the FGS sensor, the last original instrument on the HST. In addition, a cooler was installed to revive NICMOS and the solar arrays were replaced. The shuttle also boosted HST during this mission.

Developer: NASA **Country:** United States
First Use Date: 2002 **Status:** Completed
Contact vs. Non-Contact: Contact
Misalignment Tolerance: Unavailable
Max RPO Initiation Distance (m): Unavailable
Cooperative vs. Non-Cooperative: Cooperative

6.2.25 RCDM25: Servicing Mission 4 (STS-125) [HST]

Description: STS-125, the fifth and final servicing mission to HST, included the installation of WFC3 and COS instruments, repair of the STIS and ACS, replacement of rate unit sensors and batteries, and installation of a soft capture mechanism and new outer blanket layers for thermal protection.

Developer: NASA **Country:** United States

First Use Date: 2009 **Status:** Completed

Contact vs. Non-Contact: Contact

Misalignment Tolerance: Unavailable

Max RPO Initiation Distance (m): Unavailable

Cooperative vs. Non-Cooperative: Cooperative

6.2.26 RCDM26: 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:** Operational

Contact vs. Non-Contact: Non-Contact

Misalignment Tolerance: N/A

Max RPO Initiation Distance (m): Unavailable

Cooperative vs. Non-Cooperative: Unavailable

6.2.27 RCDM27: 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:** In Development

Contact vs. Non-Contact: Contact

Misalignment Tolerance: Unavailable

Max RPO Initiation Distance (m): 30

Cooperative vs. Non-Cooperative: Both

6.2.28 RCDM28: SSVP

Description: Sistema Stykivki I Vnutrennego Perekhoda

Developer: TsKBEM design bureau **Country:** Russia

First Use Date: 1971 **Status:** Operational

Contact vs. Non-Contact: Contact

Misalignment Tolerance: Unavailable

Max RPO Initiation Distance (m): Unavailable

Cooperative vs. Non-Cooperative: Unavailable

6.2.29 RCDM29: 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: 2021 **Status:** Operational

Contact vs. Non-Contact: Contact

Misalignment Tolerance: Not given, stated "significant" misalignment tolerance

Max RPO Initiation Distance (m): N/A

Cooperative vs. Non-Cooperative: Cooperative

6.2.30 RCDM30: 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:** Completed

Contact vs. Non-Contact: Non-Contact

Misalignment Tolerance: N/A

Max RPO Initiation Distance (m): Unavailable

Cooperative vs. Non-Cooperative: Non-cooperative

6.2.31 RCDM31: 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:** Completed

Contact vs. Non-Contact: Non-Contact

Misalignment Tolerance: N/A

Max RPO Initiation Distance (m): 5000

Cooperative vs. Non-Cooperative: Non-cooperative

6.3 Relocation

6.3.1 R01: Aolong-1

Description: Aolong-1 is a Chinese developed satellite which demonstrated the removal of a simulated space debris object from orbit. The satellite captured the space debris and altered the trajectory to de-orbit in Earth's atmosphere.

Developer: NUDT/PLA **Country:** China

First Use Date: 2016 **Status:** Operational

Intended Transit: debris to atmosphere for removal (assumed)

Max. Client Mass: Unavailable

Thruster / Propellant Type: Unavailable

6.3.2 R02: 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: 2021 **Status:** Operational

Intended Transit: debris removal

Max. Client Mass: 20 kg

Thruster / Propellant Type: green chemical

6.3.3 R03: 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: D-Orbit **Country:** Italy

First Use Date: 2020 **Status:** Operational

Intended Transit: change of altitude and inclination, true anomaly phasing, RAAN shift

Max. Client Mass: 160 kg

Thruster / Propellant Type: Unavailable

6.3.4 R04: ISS Reboost

Description: Throughout the lifetime of the ISS, reboost operations have been performed by visiting spacecraft, such as Progress, Shuttle, Ariane Transfer Vehicle, and through operations of the Zvezda module. These boosting operations were used on an as needed basis in order to maintain orbit.

Developer: NASA **Country:** United States

First Use Date: Unavailable **Status:** Operational

Intended Transit: LEO

Max. Client Mass: N/A

Thruster / Propellant Type: Chemical

6.3.5 R05: 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: In Development
Intended Transit: Attitude control in GEO
Max. Client Mass: Unavailable
Thruster / Propellant Type: Electric

6.3.6 R06: Mission Extension Vehicle (MEV)

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. 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: 2020
Status: Operational
Intended Transit: GEO
Max. Client Mass: Unavailable
Thruster / Propellant Type: Electric

6.3.7 R07: Mission Robotic Vehicle (MRV) [RSGS]

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: In Development
Intended Transit: GEO
Max. Client Mass: Unavailable
Thruster / Propellant Type: Electric

6.3.8 R08: 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: In Development
Intended Transit: Orbit raising and deraising, plane changes, phasing
Max. Client Mass: Assorted
Thruster / Propellant Type: Green, Hydrazine

6.3.9 R09: Orbiter

Description: Space tug developed by Launcher Space for use in LEO. First launch is expected in October 2022. The vehicle is compatible with every Cube and small satellite separation system. Orbiter expands the capability of major rideshare missions and more accurately places a spacecraft into its target orbit.

Developer: Launcher Space **Country:** United States

First Use Date: Scheduled for 2022 **Status:** In Development

Intended Transit: Orbit raising, deraising, plane changes, phasing, and inclination change in LEO

Max. Client Mass: 400 kg

Thruster / Propellant Type: Ethane and N20 chemical propulsion capable of up to 500 m/s delta-V

6.3.10 R10: Otter

Description: Otter, from Starfish Space, is a low cost, rapidly deployable ~ 200 kg space tug which will perform life extension missions in GEO and end-of-life satellite removal missions in LEO. Otter will leverage Starfish Space's CEPHALOPOD guidance and control software, to demonstrate rendezvous and proximity operations using both chemical and electric propulsion on the Tenzing satellite, which is currently on orbit. Other key components of the Otter space tug include CETACEAN, a relative navigation software, and Nautilus, a capture mechanism capable of docking without standardized, pre-installed interfaces on client satellites.

Developer: Starfish Space **Country:** United States

First Use Date: TBD **Status:** In Development

Intended Transit: Orbit maintenance in GEO, de-orbit of satellites in LEO

Max. Client Mass: Unavailable

Thruster / Propellant Type: Unavailable

6.3.11 R11: Servicing Mission 1 (STS-61) [HST]

Description: STS-61 was the first planned servicing mission of the HST. During this mission, new instruments were installed, and the primary mirror was corrected. In addition, the shuttle boosted the orbit of HST during this mission.

Developer: NASA **Country:** United States

First Use Date: 1993 **Status:** Completed

Intended Transit: Orbit raising

Max. Client Mass: N/A

Thruster / Propellant Type: Chemical

6.3.12 R12: Servicing Mission 2 (STS-82) [HST]

Description: STS-82 was the second planned servicing mission to the HST. During this mission, the shuttle crew swapped the Space Telescope Imaging Spectrograph (STIS), the Near Infrared Camera and Multi-Object Spectrometer (NICMOS), and the Fine Guidance Sensor 1 (FGS1) for outdated instruments, the Goddard High Resolution Spectrograph, the Faint Object Spectrograph, and the FGS, respectively. In addition, the Solid State Recorder (SSR) replaced the HST reel-to-reel recorders and one of the four Reaction Wheel Assemblies (RWA) was replaced with a refurbished spare. The shuttle also boosted HST during this mission.

Developer: NASA
Country: United States
First Use Date: 1997
Status: Completed
Intended Transit: Orbit raising
Max. Client Mass: N/A
Thruster / Propellant Type: Chemical

6.3.13 R13: Servicing Mission 3B (STS-109) [HST]

Description: During STS-109, the fourth servicing mission to HST, a new instrument, the FOC, replaced the FGS sensor, the last original instrument on the HST. In addition, a cooler was installed to revive NICMOS and the solar arrays were replaced. The shuttle also boosted HST during this mission.

Developer: NASA
Country: United States
First Use Date: 2002
Status: Completed
Intended Transit: Orbit raising
Max. Client Mass: N/A
Thruster / Propellant Type: Chemical

6.3.14 R14: SHERPA

Description: Spaceflight's orbital transfer vehicles are based on a 24" ESPA-class deployment system. The base unit, SHERPA-FX, was first flown in 2021 and is able to host multiple payloads, provide telemetry, and deploy at different timings during the mission. The SHERPA-AC model additionally provides a flight computer, attitude knowledge and control, and is optimized for hosted payloads. The SHERPA-LTC model features a high thrust propulsion system from Benchmark Space Systems, which provides the ability to rapidly transfer orbits. The SHERPA-LTE model, first flown in 2021 on SXRS-5, addresses LTAN and plane changes, provides electric propulsion, and has the capability to deliver spacecraft to GEO, Cislunar, or Earth-escape orbits. The final variant, the SHERPA-ES, is expected to fly in 2022 and provides high delta-V for satellite delivery anywhere in cislunar space.

Developer: Spaceflight
Country: United States
First Use Date: 2021
Status: Operational
Intended Transit: Orbit raising and lowering, in-plane phasing, LTAN,
Max. Client Mass: Unavailable
Thruster / Propellant Type: Bi-propellant, green propulsion, Chemical Propulsion, electric propulsion, Xenon propellant

6.3.15 R15: 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 serve as a payload bus.

Developer: Firefly Aerospace **Country:** United States

First Use Date: TBD **Status:** In Development

Intended Transit: Orbit raising and deraising, plane changes, phasing

Max. Client Mass: 800 kg

Thruster / Propellant Type: solar-electric

6.3.16 R16: Vigoride

Description: Vigoride, the first space tug from Momentus, is compatible with ESPA Grande and designed for orbital plane changes, inclination adjustments, and payload delivery.

Developer: Momentus **Country:** United States

First Use Date: TBD **Status:** In Development

Intended Transit: Orbit raising and deraising mainly in low earth orbits

Max. Client Mass: 750 kg

Thruster / Propellant Type: water plasma engines

6.4 Planned Repair, Upgrade, Maintenance, Installation

6.4.1 PRUMI01: 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: TBD **Status:** In Development
Operation Type: Modular Interface
ORU SWaP: Unavailable
Standard Interface Type: Unavailable

6.4.2 PRUMI02: 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: 1/1/2021 **Status:** Operational
Operation Type: Grapple interface
ORU SWaP: Unavailable
Standard Interface Type: Mechanical

6.4.3 PRUMI03: FuseBlox

Description: FuseBlox is an androgynous interface for mechanical, electrical, and data. Received Phase II SBIR funding from AFRL.
Developer: SpaceWorks **Country:** United States
First Use Date: TBD **Status:** In Development
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 PRUMI04: GOLD-2 Connector [ISS]

Description: General purpose latching device suitable for mechanically connecting up 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: 7/1/2020 **Status:** Operational
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 PRUMI05: 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: TBD **Status:** In Development

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 PRUMI06: 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: TBD **Status:** In Development

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

6.4.7 PRUMI07: 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: TBD **Status:** In Development

Operation Type: Modular Interface

ORU SWaP: Unavailable

Standard Interface Type: Mechanical

6.4.8 PRUMI08: 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: Completed
Operation Type: Servicer
ORU SWaP: Unavailable
Standard Interface Type: Data, Power, Mechanical

6.4.9 PRUMI09: Servicing Mission 1 (STS-61) [HST]

Description: STS-61 was the first planned servicing mission of the HST. During this mission, new instruments were installed, and the primary mirror was corrected. In addition, the shuttle boosted the orbit of HST during this mission.

Developer: NASA
Country: United States
First Use Date: 1993
Status: Completed
Operation Type: Servicer
ORU SWaP: Unavailable
Standard Interface Type: N/A

6.4.10 PRUMI10: Servicing Mission 2 (STS-82) [HST]

Description: STS-82 was the second planned servicing mission to the HST. During this mission, the shuttle crew swapped the Space Telescope Imaging Spectrograph (STIS), the Near Infrared Camera and Multi-Object Spectrometer (NICMOS), and the Fine Guidance Sensor 1 (FGS1) for outdated instruments, the Goddard High Resolution Spectrograph, the Faint Object Spectrograph, and the FGS, respectively. In addition, the Solid State Recorder (SSR) replaced the HST reel-to-reel recorders and one of the four Reaction Wheel Assemblies (RWA) was replaced with a refurbished spare. The shuttle also boosted HST during this mission.

Developer: NASA
Country: United States
First Use Date: 1997
Status: Completed
Operation Type: Servicer
ORU SWaP: Unavailable
Standard Interface Type: N/A

6.4.11 PRUMI11: Servicing Mission 3A (STS-103) [HST]

Description: STS-103 was the third servicing mission of the HST. During this mission, astronauts replaced 4 failed and 2 working RWAs with new models; Installed a new FGS, VIK, spare SSR, and SSAT; and replaced HST's computer, NOBL, and SSRF. New thermal insulation blankets were also installed.

Developer: NASA
Country: United States
First Use Date: 1999
Status: Completed
Operation Type: Servicer
ORU SWaP: Unavailable
Standard Interface Type: N/A

6.4.12 PRUMI12: Servicing Mission 3B (STS-109) [HST]

Description: During STS-109, the fourth servicing mission to HST, a new instrument, the FOC, replaced the FGS sensor, the last original instrument on the HST. In addition, a cooler was installed to revive NICMOS and the solar arrays were replaced. The shuttle also boosted HST during this mission.

Developer: NASA
Country: United States
First Use Date: 2002
Status: Completed
Operation Type: Servicer
ORU SWaP: Unavailable
Standard Interface Type: N/A

6.4.13 PRUMI13: Servicing Mission 4 (STS-125) [HST]

Description: STS-125, the fifth and final servicing mission to HST, included the installation of WFC3 and COS instruments, repair of the STIS and ACS, replacement of rate unit sensors and batteries, and installation of a soft capture mechanism and new outer blanket layers for thermal protection.

Developer: NASA
Country: United States
First Use Date: 2009
Status: Completed
Operation Type: Servicer
ORU SWaP: Unavailable
Standard Interface Type: N/A

6.4.14 PRUMI14: SLEGO Architecture

Description: The SLEGO block is a high performance, modular spacecraft bus which is capable of interfacing with payloads attached to a SLEGO interface or with other SLEGO building blocks. Each SLEGO block manages power, provides basic sensing and metrology, processes and manages data, provides basic attitude adjustments, and manages thermal control. Fluids for thermal or refueling purposes can be transmitted through the modular interface. This interface has been tested through the eXCITe (eXperiment for Cellular Integration Technology) mission launched to LEO in 2018, the Satlet Initial-Mission Proofs and Lessons (SIMPL) mission on the ISS in 2017, and the PODSat-1 mission launched within DARPA's Hosted POD Assembly in GEO.

Developer: NovaWurks **Country:** United States

First Use Date: 2017 **Status:** Operational

Operation Type: Modular Interface

ORU SWaP: Unavailable

Standard Interface Type: Mechanical, Fluid, Power, Data

6.4.15 PRUMI15: 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: N/A **Status:** Concluded

Operation Type: Repair servicer

ORU SWaP: SOUL Unit stow in 6U container, has a mass of <10kg and peak power of <100W.

Standard Interface Type: N/A

6.4.16 PRUMI16: 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: TBD **Status:** In Development

Operation Type: Modular Interface

ORU SWaP: Interface Mass: 1.5 kg, Max Lateral load: 270 Nm, Power: 2400 W, Data: 1000 Mbps, Thermal: 2-2.5 kW

Standard Interface Type: Mechanical, Fluid(Thermal), Power, Data

6.4.17 PRUMI17: The Puck & Service Pods

Description: The Puck, 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: TBD **Status:** In Development

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 ULRM01: 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:** In Development

Repairable Subsystems / Components: Refueling, deorbiting constellations, assembly of systems, delivery and integration of payloads

Repair Tools: Kraken Robotic Arm

Grapple Types: Kraken Robotic Arm, Unavailable

6.5.2 ULRM02: 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: Scheduled for 2024 **Status:** In Development

Repairable Subsystems / Components: Unavailable

Repair Tools: None in current design (planned for future)

Grapple Types: Unavailable

6.5.3 ULRM03: Mission Robotic Vehicle (MRV) [RSGS]

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:** In Development

Repairable Subsystems / Components: Unavailable

Repair Tools: DARPA's two dexterous robotic manipulator arms, several tools and sensors

Grapple Types: Unavailable

6.5.4 ULRM04: 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: Scheduled for 2025 **Status:** In Development

Repairable Subsystems / Components: Refueling, others unavailable

Repair Tools: Dexterous Robotc Arms (2), Space Infrastructure Dexterous Robot (SPIDER), Autonomous Real-time Relative Navigation System, Servicing Avionics, Advanced Tool Drive and Tools, Propellant Transfer System

Grapple Types: 2 robotic arms, SPIDER arm

6.5.5 ULRM05: Robotic Refueling Mission 2 (RRM2)

Description: In 2015, RRM was embarking on a new set of operations that might not be connected with robotic refueling - but have everything to do with extending and enhancing the operational lives of existent and future satellites in orbit. Building on its team's experience base, RRM worked through an updated to-do list that includes testing a new inspection tool, practicing intermediary steps leading up to coolant replenishment, testing electrical connections for "plug-and-play" space instruments, and working with decals that could help operations guided by machine vision go more smoothly. What's the common thread? Servicing capabilities. These new technologies, tools and techniques could eventually give satellite owners resources to diagnose problems on orbit, fix anomalies, and keep certain spacecraft instruments performing longer in space. Phase 2 of RRM operations began in May 2015 with Dextre, the Canadian Space Agency's two-handed robot, transferring new RRM hardware - two task boards and a multi-purpose inspection tool - to the RRM module.

Developer: NASA **Country:** United States

First Use Date: 2015 **Status:** Completed

Repairable Subsystems / Components: Coolant replenishment, testing electrical connections, working with machine vision indicators.

Repair Tools: Dextre, VIPIR, Wire Cutter and Blanket Manipulation Tool, Multifunction Tool, Safety Cap Tool, and Nozzle Tool

Grapple Types: Dextre

6.5.6 ULRM06: Servicing Mission 2 (STS-82) [HST]

Description: STS-82 was the second planned servicing mission to the HST. During this mission, the shuttle crew swapped the Space Telescope Imaging Spectrograph (STIS), the Near Infrared Camera and Multi-Object Spectrometer (NICMOS), and the Fine Guidance Sensor 1 (FGS1) for outdated instruments, the Goddard High Resolution Spectrograph, the Faint Object Spectrograph, and the FGS, respectively. In addition, the Solid State Recorder (SSR) replaced the HST reel-to-reel recorders and one of the four Reaction Wheel Assemblies (RWA) was replaced with a refurbished spare. The shuttle also boosted HST during this mission.

Developer: NASA **Country:** United States

First Use Date: 1997 **Status:** Completed

Repairable Subsystems / Components: Instrument swap and hardware upgrade.

Repair Tools: Canadarm, EVA tools

Grapple Types: Canadarm

6.5.7 ULRM07: Servicing Mission 4 (STS-125) [HST]

Description: STS-125, the fifth and final servicing mission to HST, included the installation of WFC3 and COS instruments, repair of the STIS and ACS, replacement of rate unit sensors and batteries, and installation of a soft capture mechanism and new outer blanket layers for thermal protection.

Developer: NASA **Country:** United States

First Use Date: 2009 **Status:** Completed

Repairable Subsystems / Components: Instrument swap, repair, sensor replacement, new hardware installation

Repair Tools: Canadarm, EVA tools

Grapple Types: Canadarm

6.5.8 ULRM08: Wire Cutter Tool [RRM]

Description: The Wire Cutter Tool's precision and fine-grabbing capabilities allow it to both snip tiny wires and safely move aside delicate thermal blankets. A spade bit on the tool's tip can slice blanket tape. Its parallel jaw grippers are able to grab a satellite's appendages. The Wire Cutter Tool has a functionality of four: it grabs, it snips, it manipulates, and it slices. This tool is part of the RRM 1 tool suite.

Developer: NASA **Country:** United States

First Use Date: 2013 **Status:** Completed

Repairable Subsystems / Components: N/A

Repair Tools: N/A

Grapple Types: Small snipper, slicer, and manipulator

6.6 Refueling and Fluid Transfer

6.6.1 RFT01: Cryogenic Servicing Tool (CST) [RRM]

Description: A robotic tool with adjustable rollers used to grab a flexible cryogen transfer hose and install it into a fuel port. Used on RRM 3.

Developer: NASA
Country: United States
First Use Date: 2018
Status: Completed
Propellant / Fluid Type: Methane
Fuel Volume / Mass: 42 liters
Boil - Off Rate: ~Zero

6.6.2 RFT02: 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: Completed
Propellant / Fluid Type: Water
Fuel Volume / Mass: Approx. 15 liters
Boil - Off Rate: N/A

6.6.3 RFT03: 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 1.6 liters per minute. FARE-II again used colored water.

Developer: NASA MSFC
Country: United States
First Use Date: 1993
Status: Completed
Propellant / Fluid Type: Water
Fuel Volume / Mass: 16.8 liters
Boil - Off Rate: N/A

6.6.4 RFT04: Furphy Prototype Tanker [ISS]

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: Completed
Propellant / Fluid Type: Water
Fuel Volume / Mass: 15 liters
Boil - Off Rate: N/A

6.6.5 RFT05: Multi-Function Tool 2 (MFT2) [RRM]

Description: A dual rotary drive tool used to connect custom hose adapters to robot-friendly fill ports. Used on RRM 3.

Developer: NASA
Country: United States
First Use Date: 2018
Status: Completed
Propellant / Fluid Type: N/A
Fuel Volume / Mass: N/A
Boil - Off Rate: N/A

6.6.6 RFT06: Multifunction Tool [RRM]

Description: The Multifunction Tool, part of the RRM 1 tool suite, effectively does the work of four tools. It connects with four unique adapters to capture and remove three distinct caps and remove one gas "plug" on the RRM module.

Developer: NASA
Country: United States
First Use Date: 2011
Status: Completed
Propellant / Fluid Type: N/A
Fuel Volume / Mass: N/A
Boil - Off Rate: N/A

6.6.7 RFT07: 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: In Development
Propellant / Fluid Type: LOX, LH2
Fuel Volume / Mass: 10 t (SpaceX demo), TBD for others
Boil - Off Rate: Unavailable

6.6.8 RFT08: Nozzle Tool [RRM]

Description: The Nozzle Tool connects to, opens and ultimately closes a satellite fuel valve. Using an attached hose, it transfers a representative satellite fuel in a continuous loop to simulate the refueling of a satellite. The Nozzle Tool has an anti-cross-threading feature that ensures it cannot damage the satellite fuel valve by screwing the fuel cap on the wrong way. The fuel cap that the tool leaves behind has a "quick disconnect" fitting that gives operators easy future access to the valve, should it be needed. This tool is part of the RRM 1 tool suite.

Developer: NASA
Country: United States
First Use Date: 2011
Status: Completed
Propellant / Fluid Type: N/A
Fuel Volume / Mass: N/A
Boil - Off Rate: N/A

6.6.9 RFT09: 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: Completed
Propellant / Fluid Type: Hydrazine
Fuel Volume / Mass: Unknown
Boil - Off Rate: N/A

6.6.10 RFT10: 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 to inflate a bladder.

Developer: NASA JSC
Country: United States
First Use Date: 1984
Status: Completed
Propellant / Fluid Type: Hydrazine
Fuel Volume / Mass: 142 kg
Boil - Off Rate: N/A

6.6.11 RFT11: 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: Planned for 2025
Status: In Development
Propellant / Fluid Type: Hydrazine
Fuel Volume / Mass: Unknown
Boil - Off Rate: N/A

6.6.12 RFT12: Progress Vehicle and ATV Refueling of ISS [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 was 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: Completed
Propellant / Fluid Type: NTO, UDMH, Water
Fuel Volume / Mass: up to 1740 kg
Boil - Off Rate: N/A

6.6.13 RFT13: Robotic Refueling Mission 1 (RRM1)

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: 2011
Status: Completed
Propellant / Fluid Type: Ethanol
Fuel Volume / Mass: 1.7 liters
Boil - Off Rate: Unavailable

6.6.14 RFT14: 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:** Completed
Propellant / Fluid Type: Methane
Fuel Volume / Mass: 42 liters
Boil - Off Rate: ~Zero

6.6.15 RFT15: Safety Cap Tool [RRM]

Description: The Safety Cap Tool is used on RRM 1. It removes and stows a typical fuel-valve safety cap and its seal. Small adapters allow it to also manipulate screws and remove caps on the RRM module. Each RRM tool's lobster-like appearance comes from the two integral cameras with built-in LEDs, which image and illuminate the tool's work during mission operations.

Developer: NASA **Country:** United States
First Use Date: 2011 **Status:** Completed
Propellant / Fluid Type: N/A
Fuel Volume / Mass: N/A
Boil - Off Rate: N/A

6.6.16 RFT16: SLEGO Architecture

Description: The SLEGO block is a high performance, modular spacecraft bus which is capable of interfacing with payloads attached to a SLEGO interface or with other SLEGO building blocks. Each SLEGO block manages power, provides basic sensing and metrology, processes and manages data, provides basic attitude adjustments, and manages thermal control. Fluids for thermal or refueling purposes can be transmitted through the modular interface. This interface has been tested through the eXCITe (eXperiment for Cellular Integration Technology) mission launched to LEO in 2018, the Satlet Initial-Mission Proofs and Lessons (SIMPL) mission on the ISS in 2017, and the PODSat-1 mission launched within DARPA's Hosted POD Assembly in GEO.

Developer: NovaWurks **Country:** United States
First Use Date: 2017 **Status:** Operational
Propellant / Fluid Type: Inert gasses, green fuels, butane, refrigerants
Fuel Volume / Mass: N/A
Boil - Off Rate: N/A

6.6.17 RFT17: 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: Completed
Propellant / Fluid Type: Water
Fuel Volume / Mass: 16.8 liters
Boil - Off Rate: N/A

6.6.18 RFT18: 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: Completed
Propellant / Fluid Type: Helium
Fuel Volume / Mass: 152 liters
Boil - Off Rate: > 0

6.6.19 RFT19: 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 Tenzig 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: Operational
Propellant / Fluid Type: High-Test Peroxide (HTP)
Fuel Volume / Mass: Unavailable
Boil - Off Rate: N/A

6.6.20 RFT20: Tianyuan 1 refueling demonstration

Description: Launched in 2016 aboard a Long March-7, the Tianyuan 1 spacecraft demonstrated satellite refueling in orbit.

Developer: National University of Defense Technology
Country: China
First Use Date: 2016
Status: Completed
Propellant / Fluid Type: Unavailable
Fuel Volume / Mass: Unavailable
Boil - Off Rate: Unavailable

6.7 Structural Manufacturing and Assembly

6.7.1 SMA01: Androgynous Fasteners [ARMADAS]

Description: Androgynous fastener for autonomous robotic assembly of high performance structures. The design prioritizes ease of assembly through simple actuation with large driver positioning tolerance requirements. The mechanical connection has high strength and stiffness per mass and is reversible.

Developer: NASA **Country:** United States

First Use Date: TBD **Status:** In Development

Max. Dimensions: Nominal 20mm per fastener, 300mm per modular interface (4 fasteners). System is material supply governed, demonstrated at 5.8m

Repair Tools: (C)FPR, adaptable to metals

Joining: Androgynous Joints

Assembly Agent: Robot

Operation Regime: On-Orbit, In-Space, Terrestrial

Technology Area: Structure Joint

6.7.2 SMA02: 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. The ARMADAS project seeks provide integrated system design to address the full lifecycle of a persistent asset or surface structure. Project structural assembly systems and robots are specifically designed for energy efficient re-use, upgrade, and recycling, reconfiguration, simplified robotic manipulation, simplified 'spare part' problem for inspection and maintenance. Ground demonstration of autonomous primary structure assembly in 2022 will be followed by development of outfitting technologies.

Developer: NASA **Country:** United States

First Use Date: TBD **Status:** In Development

Max. Dimensions: System is material supply governed, demonstrated at 5.8m

Materials Type(s): Demonstrated with (C)FRP, adaptable to metals, ceramics

Joining: Robotically actuated mechanical fasteners

Assembly Agent: Robot

Operation Regime: On-Orbit, In-Space, Terrestrial

Technology Area: Robotic Assembly

6.7.3 SMA03: 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: United States
First Use Date: TBD
Status: In Development
Max. Dimensions: "Scalable"
Materials 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 SMA04: CAS [ISS]

Description: Common Attachment System - First used between ESP3 logistics carrier and the P3 zenith CAS suite.

Developer: NASA
Country: United States
First Use Date: 2009
Status: Operational
Max. Dimensions: Contact
Materials Type(s): Metal Structure
Joining: Module Joint
Assembly Agent: Robot / EVA
Operation Regime: On-Orbit
Technology Area: Structure Joint

6.7.5 SMA05: 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: United States
First Use Date: 1985
Status: Completed
Max. Dimensions: 3.7m tetrahedral truss
Materials Type(s): Metal Structure
Joining: Nodal Joints
Assembly Agent: Human
Operation Regime: On-Orbit, ISS
Technology Area: Human Assembly

6.7.6 SMA06: ESAMM

Description: Extended Structure Additive Manufacturing Machine (ESAMM) is the subsystem that additively manufactures the extended structures for OSAM-2.

Developer: Redwire
Country: United States
First Use Date: Planned for 2023
Status: In Development
Max. Dimensions: 0.84m
Materials Type(s): Metal Structure
Joining: 3D printed
Assembly Agent: Robot
Operation Regime: On Orbit
Technology Area: Robotic Arm/Assembly

6.7.7 SMA07: 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: United States
First Use Date: N/A
Status: N/A
Max. Dimensions: Approx. 360˚ rotation
Materials Type(s): Metal Structure
Joining: N/A
Assembly Agent: N/A
Operation Regime: On-Orbit, In-Space
Technology Area: Robotic Arm Joint

6.7.8 SMA08: International Space Station Truss/Backbone [ISS]

Description: Structural Components Assembled to give ISS Frame/Support.

Developer: NASA
Country: United States
First Use Date: 1998
Status: Operational
Max. Dimensions: 110m
Materials Type(s): Metal Structure
Joining: Bolted Joints
Assembly Agent: Robot / EVA
Operation Regime: On-Orbit
Technology Area: Robotic Arm/Assembly, Human Assembly, Deployable

6.7.9 SMA09: 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: United States
First Use Date: N/A
Status: N/A
Max. Dimensions: N/A
Materials Type(s): N/A
Joining: E-Beam Welding
Assembly Agent: Robot/Human
Operation Regime: On-Orbit, In-Space
Technology Area: Structure Joint

6.7.10 SMA10: MakerSat

Description: As a part of the OSAM-1 mission, the Beam Fabricator will demonstrate the manufacturing of a 3D printed beam in space.

Developer: Tethers Unlimited
Country: United States
First Use Date: Planned for 2025
Status: In Development
Max. Dimensions: 10m Truss Fabricated
Materials Type(s): Carbon Fiber
Joining: "Extrusion with Post Assembly"
Assembly Agent: Robot
Operation Regime: On-Orbit, In-Space
Technology Area: Robotic Assembly, manufacturing

6.7.11 SMA11: MRTAS [ISS]

Description: Modified Rocketdyne Truss Attachment Mechanism.

Developer: Permanent Connection
Country: United States
First Use Date: 2006
Status: Operational
Max. Dimensions: Contact
Materials Type(s): N/A
Joining: Custom Actuator Mechanism
Assembly Agent: Robot
Operation Regime: On-Orbit, In-Space
Technology Area: Structure Joint

6.7.12 SMA12: NASA Intelligent Jigging and Assembly Robot (NINJAR)

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

Developer: NASA **Country:** United States
First Use Date: TBD **Status:** In Development
Max. Dimensions: 30 x 30 x 30 cube
Materials Type(s): Metal Structure
Joining: N/A
Assembly Agent: Robot
Operation Regime: On-Orbit, In-Space, Terrestrial
Technology Area: Robotic Assembly

6.7.13 SMA13: OSAM-2

Description: The technology demonstration, previously called Archinaut One and now OSAM-2, will manufacture and deploy one 10-meter beam and one 6-meter beam. During printing of the 10-meter beam, the system will also deploy a surrogate solar array. The manufacturing will be performed by Redwire's Extended Structure Additive Manufacturing Machine.

Developer: Redwire, MSFC **Country:** United States
First Use Date: Planned for 2024 **Status:** In Development
Max. Dimensions: 10m for ESPA class satellites
Materials Type(s): PEI/PC
Joining: 3D printed
Assembly Agent: Robot
Operation Regime: On-Orbit, In-Space
Technology Area: Robotic Assembly, manufacturing

6.7.14 SMA14: 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:** United States
First Use Date: TBD **Status:** In Development
Max. Dimensions: "Scalable"
Materials Type(s): Metal Structure
Joining: Nodal Joints
Assembly Agent: Robot
Operation Regime: On-Orbit, In-Space
Technology Area: Robotic Assembly

6.7.15 SMA15: Robotically Compatible Erectable Joint with Square Cross-Section [OSAM-1]

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. Used on the SPIDER arm of OSAM-1.

Developer: NASA
Country: United States
First Use Date: Planned for 2025
Status: In Development
Max. Dimensions: N/A
Materials Type(s): Metal Structure
Joining: N/A
Assembly Agent: N/A
Operation Regime: On-Orbit, In-Space, Terrestrial
Technology Area: Robotic Arm Joint

6.7.16 SMA16: RTAS [ISS]

Description: Rocketdyne Truss Attachment System - First demonstrated when connecting ITS-P6 to Z1 on STS-97.

Developer: Permanent Connection
Country: United States
First Use Date: 2000
Status: Operational
Max. Dimensions: Contact
Materials Type(s): Metal Structure
Joining: Module Joint
Assembly Agent: Robot / EVA
Operation Regime: On-Orbit
Technology Area: Structure Joint

6.7.17 SMA17: Salyut-7 Welding Experiment

Description: During the Salyut-7 mission, astronauts welded, brazed, coated, and cut metallics using a hand-held electron beam gun. This was the first demonstration of astronaut welding during extravehicular activity.

Developer: USSR
Country: USSR
First Use Date: 1984
Status: Completed
Max. Dimensions: N/A
Materials Type(s): Metal
Joining: Welding
Assembly Agent: Human
Operation Regime: On-Orbit
Technology Area: Welding

6.7.18 SMA18: 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 in the deployed configuration.

Developer: NASA
Country: United States
First Use Date: TBD
Status: In Development
Max. Dimensions: "Scalable"
Materials Type(s): Composite
Joining: N/A
Assembly Agent: N/A
Operation Regime: On-Orbit, In-Space
Technology Area: Deployable

6.7.19 SMA19: Skylab Materials Processing Facility Experiments

Description: This facility, developed by Westinghouse, was installed on Skylab and demonstrated electron beam welding. Welds were conducted in a chamber with variable access to the space environment. Welding was conducted on Stainless Steel, Aluminum, and Tantalum at various travel speeds and electron beam parameters.

Developer: NASA/Westinghouse
Country: United States
First Use Date: 1973
Status: Completed
Max. Dimensions: 40 cm welding chamber
Materials Type(s): Metal
Joining: Welding
Assembly Agent: Human
Operation Regime: On-Orbit
Technology Area: Welding

6.7.20 SMA20: SLEGO Architecture

Description: The SLEGO block is a high performance, modular spacecraft bus which is capable of interfacing with payloads attached to a SLEGO interface or with other SLEGO building blocks. Each SLEGO block manages power, provides basic sensing and metrology, processes and manages data, provides basic attitude adjustments, and manages thermal control. Fluids for thermal or refueling purposes can be transmitted through the modular interface. This interface has been tested through the eXCITe (eXperiment for Cellular Integration Technology) mission launched to LEO in 2018, the Satlet Initial-Mission Proofs and Lessons (SIMPL) mission on the ISS in 2017, and the PODSat-1 mission launched within DARPA's Hosted POD Assembly in GEO.

Developer: NovaWurks
Country: United States
First Use Date: 10/1/2017
Status: Operational
Max. Dimensions: "Scalable"
Materials Type(s): Metal
Joining: Custom Actuator Mechanism
Assembly Agent: Robot
Operation Regime: On-Orbit, In-Space
Technology Area: Robotic Assembly

6.7.21 SMA21: Space Infrastructure Dexterous Robot (SPIDER) [OSAM-1]

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: United States
First Use Date: Planned for 2025
Status: In Development
Max. Dimensions: 5 m
Materials Type(s): Metal Structure
Joining: N/A (end-effector)
Assembly Agent: Robot
Operation Regime: On-Orbit
Technology Area: Robotic Arm

6.7.22 SMA22: SSAS [ISS]

Description: Segment to Segment Attachment Mechanism
Developer: Permanent Connection
Country: United States
First Use Date: October 2002
Status: Operational
Max. Dimensions: Contact
Materials Type(s): Metal Structure
Joining: Module Joint
Assembly Agent: Robot / EVA
Operation Regime: On-Orbit
Technology Area: Structure Joint

6.7.23 SMA23: 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: United States
First Use Date: N/A
Status: Concluded
Max. Dimensions: N/A
Materials Type(s): Composite
Joining: Bonded
Assembly Agent: N/A
Operation Regime: N/A
Technology Area: Structure Joint

6.7.24 SMA24: 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 retrieval and attachment.

Developer: NASA
Country: United States
First Use Date: TBD
Status: In Development
Max. Dimensions: 46 in.
Materials Type(s): Metal Structure
Joining: N/A
Assembly Agent: Robot
Operation Regime: On-Orbit, In-Space, Terrestrial
Technology Area: Robotic Assembly

6.7.25 SMA25: Vulkan Experiment

Description: Vulcan was a demonstration of welding on Soyuz 6 flight. During the experiment, cosmonauts tested several methods of welding stainless steel, aluminum, and titanium in the weightless and high vacuum of space. Plasma arc, electron beam, and gas metal arc welding was tested. This experiment produced the first demonstration of on-orbit welds.

Developer: USSR
Country: USSR
First Use Date: 1969
Status: Completed
Max. Dimensions: N/A
Materials Type(s): Metal
Joining: Welding
Assembly Agent: Human
Operation Regime: On-Orbit
Technology Area: Welding

6.7.26 SMA26: xLink Robotic Arm [OSAM-2]

Description: Thee Motiv xLink robotic arm will be used during NASA's OSAM-2 mission to position 3D printed solar array elements, connect deployable solar arrays, and position the onboard 3D printer.

Developer: Motiv

Country: United States

First Use Date: Planned for 2024

Status: In Development

Max. Dimensions: "scalable"

Materials Type(s): Metal Structure

Joining: N/A (gripper only)

Assembly Agent: Robot

Operation Regime: On-Orbit

Technology Area: Robotic Arm

6.8 RECYCLING, REUSE, AND REPURPOSING

6.8.1 RRR01: 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: NASA **Country:** United States
First Use Date: TBD **Status:** In Development
Recyclable Materials / Items: Metal
Product: Metal ingots

6.8.2 RRR02: 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: NASA **Country:** United States
First Use Date: TBD **Status:** In Development
Recyclable Materials / Items: Multimaterial Polymers
Product: Multiple products, incl. filament feedstock and packaging materials

6.8.3 RRR03: ReFabricator [ISS]

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: NASA LaRC **Country:** United States
First Use Date: TBD **Status:** In Development
Recyclable Materials / Items: Thermoplastic polymers
Product: Filament feedstock for 3D printing

6.8.4 RRR04: 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: NASA **Country:** United States

First Use Date: 2009 **Status:** Operational

Recyclable Materials / Items: Thermoplastic composites with short carbon fibers

Product: Coupons

6.8.5 RRR05: 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: NASA **Country:** United States

First Use Date: 1985 **Status:** Completed

Recyclable Materials / Items: Thermally reversible polymers

Product: Panels, tubes, and other geometries made with recycled composite

6.8.6 RRR06: Systems Analysis for Repurposing Structural Composite Utilization (ReSCU) Materials

Description: Systems study to explore candidate components that can be reused on space missions. Funded by CIF/IRAD.

Developer: Redwire **Country:** United States

First Use Date: Planned for 2023 **Status:** In Development

Recyclable Materials / Items: Potentially repurposable composite components

Product: Notional drag bucket

6.9 Parts and Goods Manufacturing

6.9.1 PGM01: 3D Printed Space Reflector Antenna

Description: This patented concept by Orbital Composites enables on-demand construction of antennas through 3D printing. The 3D printed antennas are scalable in size and frequency range, from 4 GHz to 110 GHz. 3D printing of antennas coupled with on orbit 3D printing allows for rapid frequency or size alterations without requiring an antenna redesign and launch.

Developer: Orbital Composites **Country:** United States

First Use Date: TBD **Status:** In Development

End Product: Finished Part

Inputs: Earth Delivered Material

Max. Dimensions: N/A

Material Type: Polymers/Composites

Operation Regime: On-Orbit

Operator: Human / Remote Human

6.9.2 PGM02: 3D Printing in Zero G TDM [ISM]

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:** United States

First Use Date: 2014 **Status:** Completed

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

6.9.3 PGM03: Additive Manufacturing Facility (AMF) [ISM]

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:** United States

First Use Date: 2016 **Status:** Operational

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

6.9.4 PGM04: Multimaterial Fabrication Laboratory [ISM]

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, now Redwire, was the only company to continue to the next phase. 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: Redwire, Interlog, Tethers Unlimited, NASA
Country: United States
First Use Date: TBD
Status: In Development
End Product: Finished Part
Inputs: Earth Delivered Material
Max. Dimensions: 6 in. x 6 in. x 6 in. for polymers, 4.5 in. x 4.5 in. x 7 in. for metallics
Material Type: Metallics and Polymers
Operation Regime: On-Orbit (ISS)
Operator: Human, Remote Human, autonomous

6.9.5 PGM05: On-Demand Manufacturing of Electronics (ODME) [ISM]

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: United States
First Use Date: Planned for 2024
Status: In Development
End Product: Finished Assembly
Inputs: N/A
Max. Dimensions: N/A
Material Type: Polymers and Electronics
Operation Regime: On-Orbit (ISS)
Operator: Human

6.9.6 PGM06: ORB - Robotic AM Platform

Description: This scalable 3D printing concept from Orbital Composites allows for the addition of new printer platforms or robotic arms to generate larger 3D printed structures. The 3D printing platform is able to print in polymers or composites and is able to print on complex curvatures.

Developer: Orbital Composites
Country: United States
First Use Date: TBD
Status: In Development
End Product: Finished Part
Inputs: Earth Delivered Material
Max. Dimensions: 2 m x 2 m x 2 m
Material Type: Polymers/Composites
Operation Regime: On-Orbit
Operator: Human / Remote Human

6.9.7 PGM07: Redwire Regolith Print (RegISS) [ISM]

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: Redwire, NASA
Country: United States
First Use Date: TBD
Status: In Development
End Product: Finished Part
Inputs: ISRU
Max. Dimensions: N/A (likely the size of the AMF)
Material Type: regolith simulant feedstock blend
Operation Regime: On-Orbit (ISS)
Operator: Human

6.9.8 PGM08: Sintered Inductive Metal Printer with Laser Exposure (SIMPLE) [ISM]

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

Developer: Redwire, NASA
Country: United States
First Use Date: N/A
Status: Concluded
End Product: Finished Part
Inputs: Earth Delivered Material
Max. Dimensions: Unknown
Material Type: Metallic
Operation Regime: Microgravity (any NASA Vehicle)
Operator: Human

6.9.9 PGM09: Vulcan [ISM]

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: Redwire, NASA

Country: United States

First Use Date: Planned for 2024

Status: In Development

End Product: Finished Part

Inputs: Earth Delivered Material

Max. Dimensions: Unknown

Material Type: Metallics and Polymers

Operation Regime: On-Orbit (ISS)

Operator: Human

6.10 Surface Construction

6.10.1 SC01: 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: United States
First Use Date: TBD
Status: In Development
Materials (Imported v. ISRU): ISRU
Construction Agent: Robot
Auto / Fly-by-Wire / Planned: Planned

6.10.2 SC02: 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: United States
First Use Date: TBD
Status: In Development
Materials (Imported v. ISRU): ISRU
Construction Agent: Human
Auto / Fly-by-Wire / Planned: Planned

6.10.3 SC03: 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. The ARMADAS project seeks provide integrated system design to address the full lifecycle of a persistent asset or surface structure. Project structural assembly systems and robots are specifically designed for energy efficient re-use, upgrade, and recycling, reconfiguration, simplified robotic manipulation, simplified 'spare part' problem for inspection and maintenance. Ground demonstration of autonomous primary structure assembly in 2022 will be followed by development of outfitting technologies.

Developer: NASA ARC **Country:** United States

First Use Date: TBD **Status:** In Development

Materials (Imported v. ISRU): Imported and ISRU

Construction Agent: Robot

Auto / Fly-by-Wire / Planned: Auto

6.10.4 SC04: 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.

Developer: NASA JSC **Country:** United States

First Use Date: TBD **Status:** In Development

Materials (Imported v. ISRU): ISRU and possibly imported binder

Construction Agent: Robot

Auto / Fly-by-Wire / Planned: Planned

6.10.5 SC05: 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:** United States

First Use Date: TBD **Status:** In Development

Materials (Imported v. ISRU): ISRU

Construction Agent: Robot

Auto / Fly-by-Wire / Planned: Auto

6.10.6 SC06: 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.

Developer: NASA KSC **Country:** United States

First Use Date: TBD **Status:** In Development

Materials (Imported v. ISRU): ISRU and options for imported binders

Construction Agent: Unknown

Auto / Fly-by-Wire / Planned: Unknown

6.10.7 SC07: 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 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 and contour crafting. 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:** United States

First Use Date: TBD **Status:** In Development

Materials (Imported v. ISRU): ISRU

Construction Agent: Human

Auto / Fly-by-Wire / Planned: Fly by Wire

6.10.8 SC08: 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.

Developer: NASA KSC **Country:** United States

First Use Date: 2008 **Status:** Completed

Materials (Imported v. ISRU): Imported

Construction Agent: Robot

Auto / Fly-by-Wire / Planned: Planned

6.10.9 SC09: 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).

Developer: NASA LaRC **Country:** United States
First Use Date: TBD **Status:** In Development
Materials (Imported v. ISRU): Imported
Construction Agent: Robot
Auto / Fly-by-Wire / Planned: Planned

6.10.10 SC10: 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:** United States
First Use Date: TBD **Status:** In Development
Materials (Imported v. ISRU): ISRU
Construction Agent: Human
Auto / Fly-by-Wire / Planned: Planned

6.10.11 SC11: 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:** United States
First Use Date: TBD **Status:** In Development
Materials (Imported v. ISRU): ISRU and Construction
Construction Agent: Robot
Auto / Fly-by-Wire / Planned: Planned

6.10.12 SC12: 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. 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.

Developer: AI SpaceFactory, LERA, NASA KSC **Country:** United States
First Use Date: TBD **Status:** In Development
Materials (Imported v. ISRU): ISRU and possibly imported binder
Construction Agent: Robot
Auto / Fly-by-Wire / Planned: Planned

6.10.13 SC013: Redwire Regolith Print (RegISS) [ISM]

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:** United States
First Use Date: TBD **Status:** In Development
Materials (Imported v. ISRU): ISRU
Construction Agent: Robot
Auto / Fly-by-Wire / Planned: Planned

6.11 Inspection and Metrology

6.11.1 IM01: 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:** United States

First Use Date: 2019 **Status:** Completed

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 IM02: Alpha Magnetic Spectrometer (AMS-02) [ISS]

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 ray composition and flux.

Developer: US Dept of Energy, NASA **Country**: United States

First Use Date: 2011 **Status:** Operational

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 IM03: 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:** Completed

Contact: N, free-flying

Inspection Type: Visual

Resolution: High

Inspection Aides / Fiducials / Cues: SSA Sensor payload, GPS, accelerometers

Data Analysis: Autonomous

6.11.4 IM04: Bio-memetic Snake Arm Robot [ISS]

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: United States
First Use Date: TBD
Status: In Development
Contact: Y, robot-arm
Inspection Type: Visual
Resolution: High
Inspection Aides / Fiducials / Cues: Stereo vision, articulating head, ability to swap head sensors
Data Analysis: Off-board

6.11.5 IM05: Laura

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

Developer: Rogue Space Systems Corporation
Country: United States
First Use Date: Planned for 2022
Status: In Development
Contact: N, free-flying
Inspection Type: Visual
Resolution: High
Inspection Aides / Fiducials / Cues: Multispectral sensor capabilities
Data Analysis: Off-board

6.11.6 IM06: Manufacturing Health Monitoring System (MHMS) [OSAM-2]

Description: OSAM-2 Manufacturing Health Monitoring System (MHMS)

Developer: Motiv
Country: United States
First Use Date: TBD
Status: In Development
Contact: N/A
Inspection Type: Unknown
Resolution: Unknown
Inspection Aides / Fiducials / Cues: Unknown
Data Analysis: Unknown

6.11.7 IM07: Mission Extension Vehicle (MEV)

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. 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: 2/25/2020
Status: Operational
Contact: Y
Inspection Type: Unknown
Resolution: Unknown
Inspection Aides / Fiducials / Cues: Unknown
Data Analysis: Unknown

6.11.8 IM08: Mission Robotic Vehicle (MRV) [RSGS]

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: In Development
Contact: Unknown
Inspection Type: Unknown
Resolution: Unknown
Inspection Aides / Fiducials / Cues: Unknown
Data Analysis: Unknown

6.11.9 IM09: 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: Operational
Contact: N, free-flying
Inspection Type: Visual
Resolution: N/A
Inspection Aides / Fiducials / Cues: SSA Camera, ADCS sensors/software
Data Analysis: Autonomous

6.11.10 IM10: 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: Completed
Contact: Y, robot-arm
Inspection Type: Visual
Resolution: Unknown
Inspection Aides / Fiducials / Cues: GPS, ADCS, Ground Station comms
Data Analysis: Unknown

6.11.11 IM11: 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: Planned for 2025
Status: In Development
Contact: Y
Inspection Type: Visual
Resolution: Unknown
Inspection Aides / Fiducials / Cues: Unknown
Data Analysis: Unknown

6.11.12 IM12: 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: United States
First Use Date: 2020
Status: Operational
Contact: Y
Inspection Type: Voltage
Resolution: +/-0.02 ppm
Inspection Aides / Fiducials / Cues: Liquid Helium ($1000/deployment)
Data Analysis: Off-board

6.11.13 IM13: Robotic External Leak Locator (RELL) [ISS]

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: United States
First Use Date: 2015
Status: Operational
Contact: Y, robot-arm
Inspection Type: Ammonia sensor
Resolution: High
Inspection Aides / Fiducials / Cues: Mass spec, Ion vacuum pressure gauge
Data Analysis: Autonomous

6.11.14 IM14: SCOUT

Description: SCOUT helps SpaceCraft Observe and Understand Things around them. Enables on-demand, on-site inspections for space assets. SCOUT-Sat constellation enables sustainable access to anything in GEO within 6 hours, essentially serving as 24-hour security cameras.

Developer: Scout
Country: United States
First Use Date: 6/1/2021
Status: Operational
Contact: N, free-flying
Inspection Type: Visual
Resolution: High
Inspection Aides / Fiducials / Cues: Stereoscopic and Multispectral configurations
Data Analysis: Autonomous

6.11.15 IM15: Seeker [ISS]

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: United States
First Use Date: 2019
Status: Operational
Contact: N, free-flying
Inspection Type: Visual
Resolution: High
Inspection Aides / Fiducials / Cues: Elevation/Azimuth computation
Data Analysis: Autonomous (2 Hz)

6.11.16 IM16: Sonatest Veo PAUT [ISS]

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 assessment to the body of the ISS due to micrometeoroids. 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:** United States
First Use Date: 2013 **Status:** Operational
Contact: Y
Inspection Type: Ultrasonic
Resolution: 0.1 inches
Inspection Aides / Fiducials / Cues: Multi-angle top scan
Data Analysis: Off-board

6.11.17 IM17: 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:** In Development
Contact: Y, tethered
Inspection Type: Visual, near IR
Resolution: N/A
Inspection Aides / Fiducials / Cues: N/A
Data Analysis: N/A

6.11.18 IM18: Visual Inspection Poseable Invertebrate Robot (VIPIR) [RRM]

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. Used on RRM2.

Developer: NASA GSFC **Country:** United States
First Use Date: 2015 **Status:** Completed
Contact: Y, robot-arm
Inspection Type: Visual
Resolution: 224 x 224 pixel, 100 deg Fov
Inspection Aides / Fiducials / Cues: 8-24 mm optical zoom lens
Data Analysis: Off-board

6.11.19 IM19: Visual Inspection Poseable Invertebrate Robot 2 (VIPIR2) [RRM]

Description: A robotic inspection camera used to visually verify entry and positioning of the Cryogen (flexible line) Transfer Hose (CTH) into the receiver tank. Used on RRM3.

Developer: NASA GSFC
Country: United States
First Use Date: 12/8/2018
Status: Completed
Contact: Y
Inspection Type: Visual
Resolution: Unknown
Inspection Aides / Fiducials / Cues: Unknown
Data Analysis: Off-board

6.11.20 IM20: 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: Completed
Contact: N, free-flying
Inspection Type: Visual
Resolution: High
Inspection Aides / Fiducials / Cues: GPS, Star Tracker, SGLS system
Data Analysis: Autonomous

6.11.21 IM21: 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: Completed
Contact: N, free-flying
Inspection Type: Visual
Resolution: High
Inspection Aides / Fiducials / Cues: RPOD, On-orbit command/control
Data Analysis: Off-board

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