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

2023 Edition

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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 missions will not be feasible by launching an integrated, fully functioning system on a single launch vehicle. For example, future 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 to 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 to the best ability of the authors. 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 the ISS. Many more are being developed to increase autonomy, reduce cost, and expand the capability 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 a client space object with a servicing spacecraft 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 space object and ISAM servicing spacecraft 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 space object 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 technologies to reframe spacecraft components and materials as part of the "native" resources available for a 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.
- **Parts and Goods Manufacturing**: The initial capability for parts and goods 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 or lunar 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 configuration, size, shape, state of repair, or other features of interest. The systems to perform this task include free-flyer inspection, non-destructive evaluation, close (robotic) inspection, and visual or multispectral inspection.

The 2023 edition 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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Table of Acronyms

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
ASTRO	Autonomous Space Transport Robotic Operations
CHAPEA	Crew Health and Performance Analog
CNC	Computerized Numerical Control
COSMIC	Cleaning Outer Space Mission through Innovative Capture
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
ELC	Express Logistics Carrier
ELSA-d	End-of-Life Services by Astroscale Demo
ELSA-M	End-of-Life Service by Astroscale - Multiple
ESAMM	Extended Structure Additive Manufacturing Machine
ESPA	EELV Secondary Payload Adapter
ETS	Engineering Test Satellite
EVA	Extravehicular Activity
EVR	Extravehicular Robotic
eXCITe	eXperiment for Cellular Integration Technology
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
FFRDC	Federally funded research and development center
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
IVA	Intravehicular Activity
IVR	Intravehicular Robotic
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
MEP	Mission Extension Pod
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
N2H4	Hydrazine
NASDA	National Space Development Agency of Japan
NEXTSat	Next Generation Satellite and Commodities Spacecraft
NINJAR	NASA Intelligent Jigging and Assembly Robot
NTO	Nitrogen Tetroxide
OMV	Orbital Maneuvering Vehicle
ORS	Orbital Refueling System
ORU	Orbital Replacement Unit
OSAM	On-orbit Servicing, Assembly, and Manufacturing
PASS	Precision Assembled Space Structures
PAUT	Phased Array Ultrasonic Test
PODSAT 1	Payload Orbital Delivery Satellite
RASSOR	Regolith Advanced Surface Systems Operations Robot
REACT	Relevant Environment Additive Construction Technology
RegISS	Redwire Regolith Print
RELL	Robotic External Leak Locator
RiTS	Robotic Tool Stowage
RSV	Robotic servicing vehicle
ROSA	Roll out Solar Arrays
RPO	Rendezvous and Proximity Operations
RRM3	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
SIMPL	Satlet Initial-Mission Proofs and Lessons
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
STP	Space Test Program
STS	Space Transportation System
SUV	Space Utility Vehicle
TCAM	Twisted and Coiled Artificial Muscles
TALISMAN	Tendon-Actuated Lightweight In-Space MANipulator
TDM	Technology Demonstration Mission
TLT	Tall Lunar Tower
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. Realizing these ambitious missions is not feasible using the traditional paradigm. For example, future 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, relocation, 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 lifespan 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 space operations, 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 has enabled ambitious space missions. The assembly and maintenance of the ISS, the repair of the Alpha Magnetic Spectrometer instrument, the servicing operations 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 the flight demonstrations that have advanced ISAM capabilities. These missions are further detailed and correlated with ISAM Activities in Section 5.

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 demonstrated various manufacturing capabilities inside the pressurized volume.

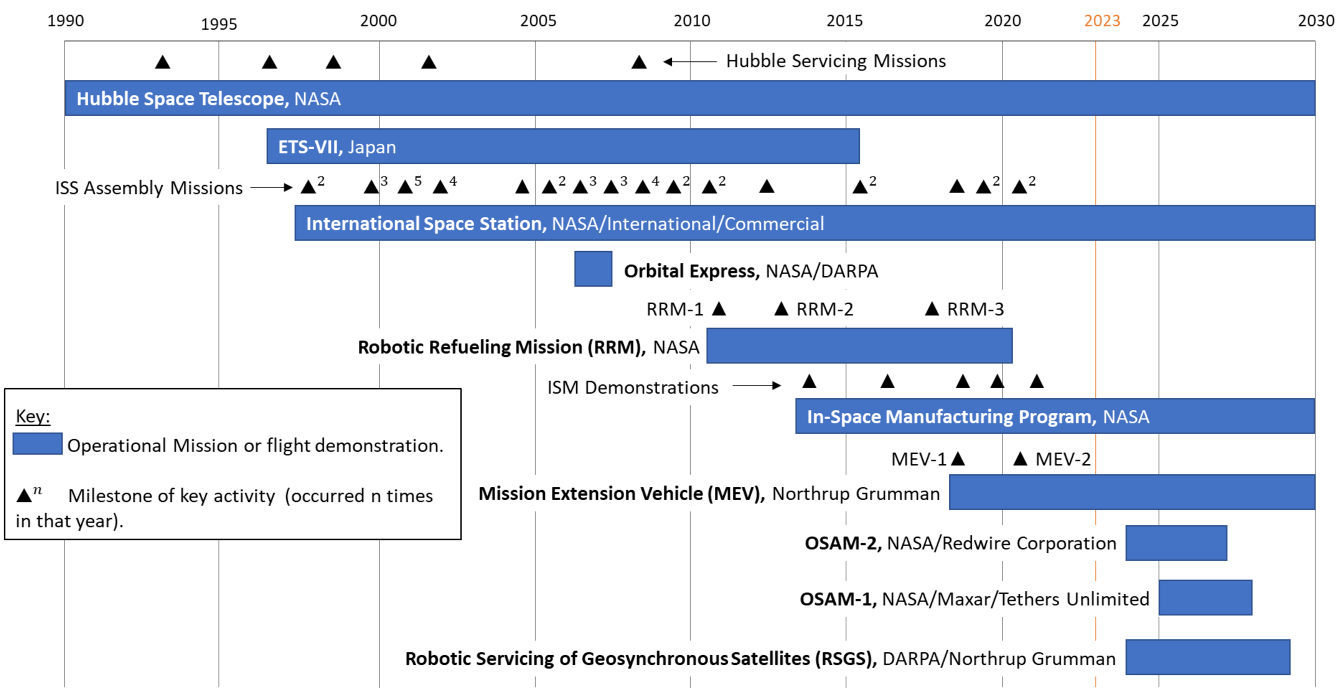

Figure 1: There is a long history of ISAM capabilities being used and advanced in ambitious operational missions (e.g., ISS, Hubble, and MEV) and flight demonstrations (e.g., Orbital Express). These missions and demonstrations have been performed by civil, national security, and commercial space organizations.

3 ISAM CAPABILITY AREAS

This document organizes the identified ISAM missions, capabilities, and developments 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 may be performed during an ISAM-enabled mission, 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 client space object that is prepared to receive those components. These operations are performed 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 client space object 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 fabricating 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 producing 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 Section 5 breaks down the specific activities or subsystems from each mission that demonstrated the capability areas identified in Figure 2. Through its assembly and servicing operations, 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.

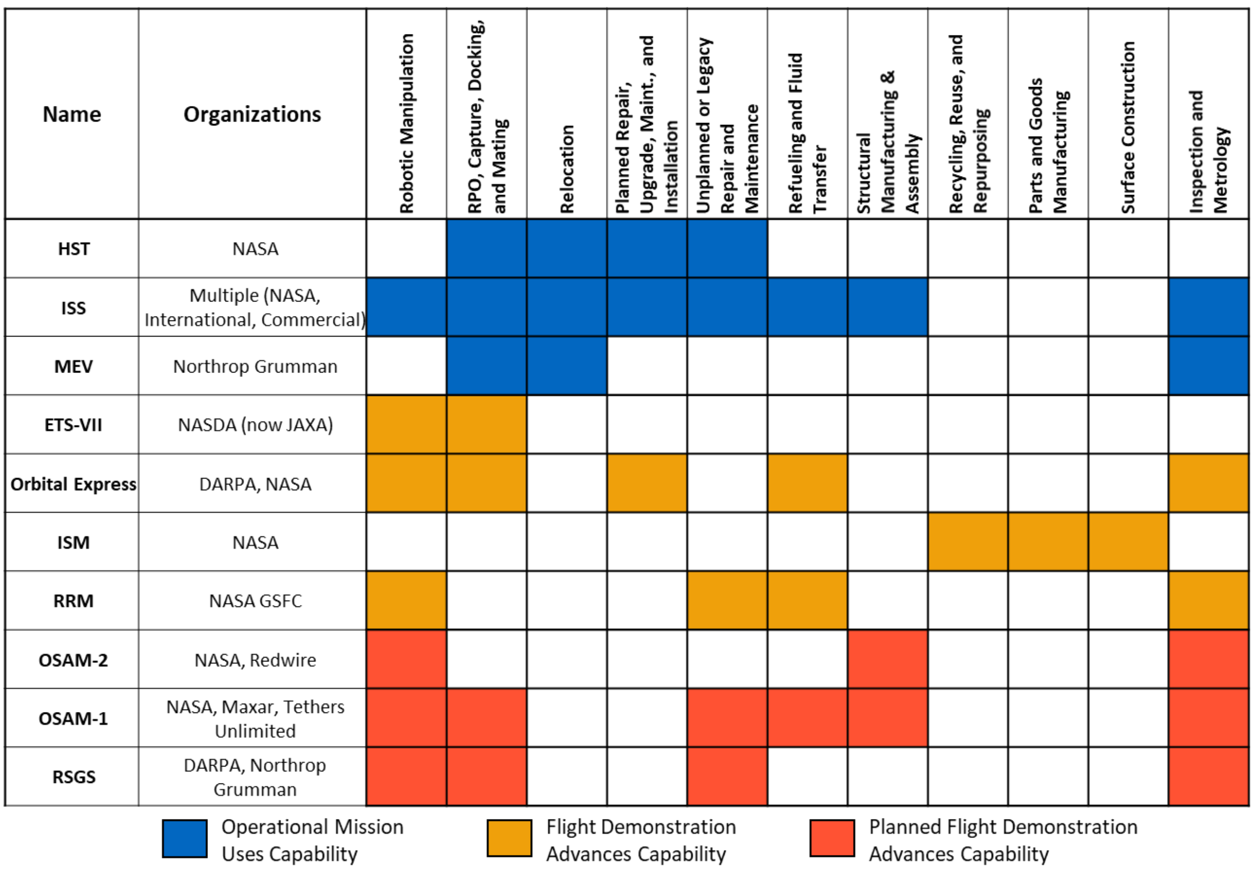

Figure 2: Operational missions and flight demonstrations have used and advanced ISAM capabilities, and planned missions will demonstrate more. Robotic Manipulation; RPO, Capture, Docking, and Mating; and Inspection and Metrology capability areas have been used in most of these missions, and the ISS has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

The purpose of this document is to continuously collect previous and ongoing ISAM development activities, technologies, and facilities 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. Robotic Manipulation and RPO, Capture, Docking, and Mating are the most prolific, and many of the nascent or forward-looking capability areas, such as Recycling, Reuse, and Repurposing, have fewer activities.

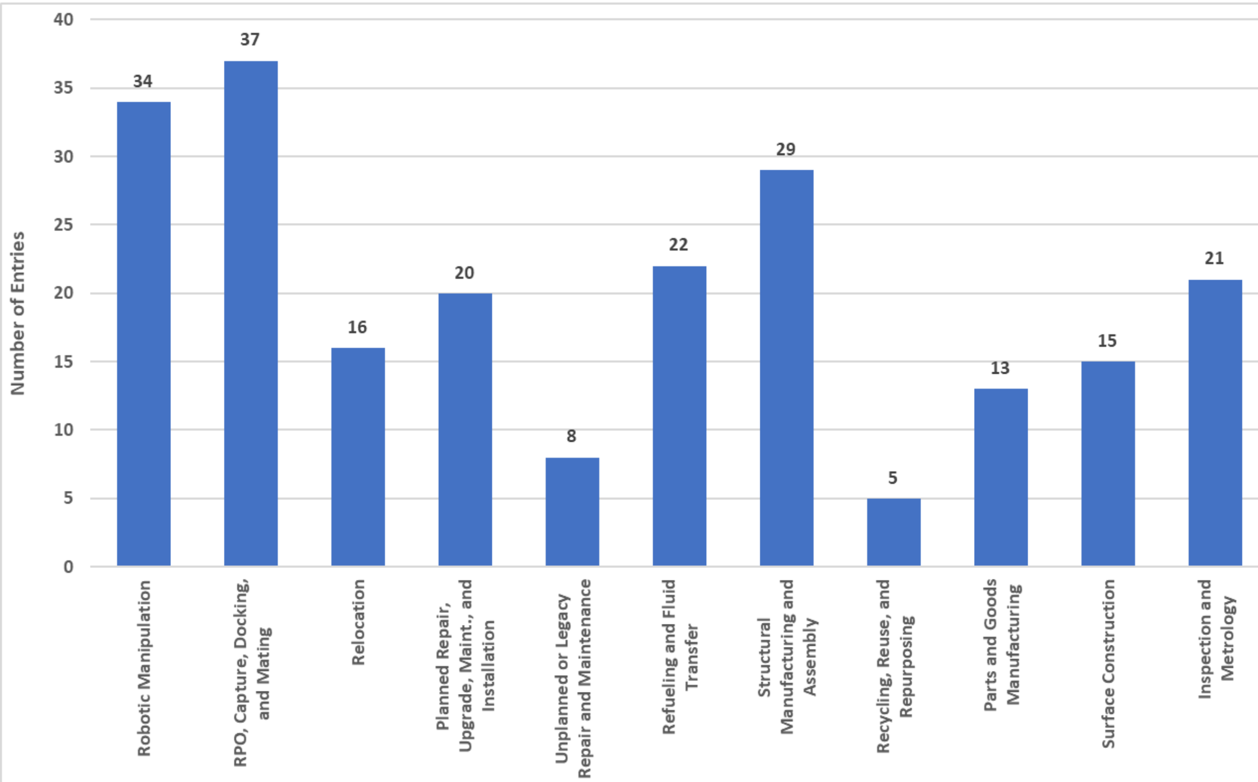

Figure 3: The activities or technologies collected in this document are categorized into the capability areas. This bar chart represents the number of activities in each capability area.

Each capability area section contains an overview and the current state 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 insight into the current state and future direction of capability area development. Additional details on the entries for each capability area can be found in Section 7, 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 space objects. 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 classes 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 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 through operation on Shuttle and the ISS. 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 in robotic manipulation are focused on increased capability and reduced cost. 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, such as the NASA Servicing Arm, the FREND arm, and the GITAI S2, are in development to support servicing, assembly, and manufacturing in space. The ARMADAS and GITAI robotic arms, similar to the Canadarm, are capable of repositioning autonomously to expand their working envelope and further support assembly or servicing tasks. 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.

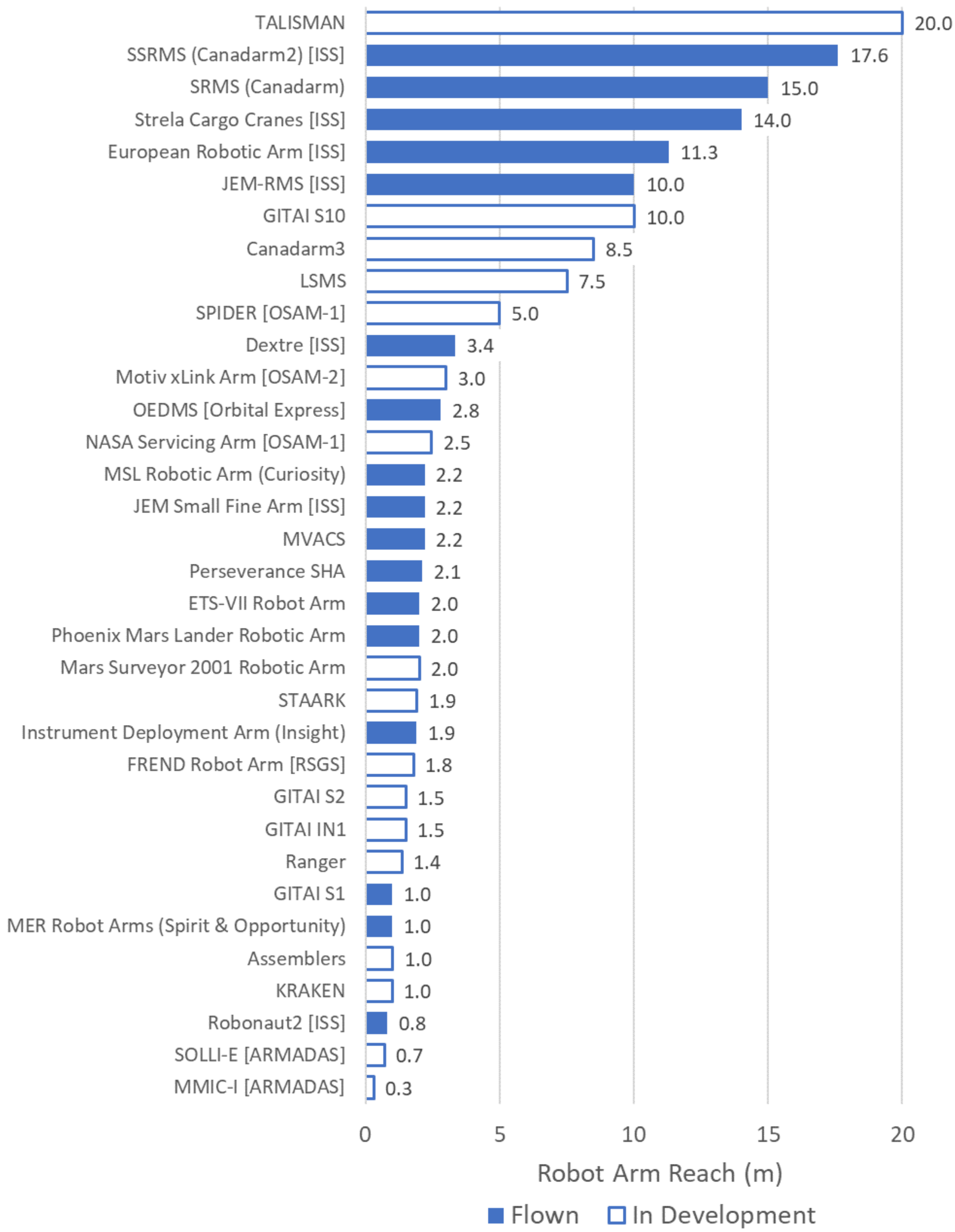

Figure 4: Robotic manipulators have flown for a variety of missions, from surface robotics to long reach manipulation on the ISS. Many are being developed to increase autonomy, reduce cost, and proliferate the use of space robotics. This figure displays the baseline configuration length for variable 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 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 spacecraft and is therefore a necessary first step for many ISAM operations, 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 the most cross-listed capability area, 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 uncrewed Kosmos 186 and the uncrewed 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, Cygnus, Cargo Dragon, Crew Dragon, and Starliner.

Major advancement towards fully autonomous mating of uncrewed spacecraft has been in progress since the Japanese ETS-VII mission in 1998, which demonstrated utility for uncrewed 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 in 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 spacecraft that maneuver, transfer fuel, or complete repairs on incapacitated satellites must first perform RPO, capture, docking, and mating operations. To that end, the state-of-the-art for this capability area has recently advanced through the development of servicing spacecraft, such as Northrop Grumman's MEV-1 and MEV-2 and Starfish Space's Otter. The 200-kg 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 distribution of target spacecraft sizes for 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.

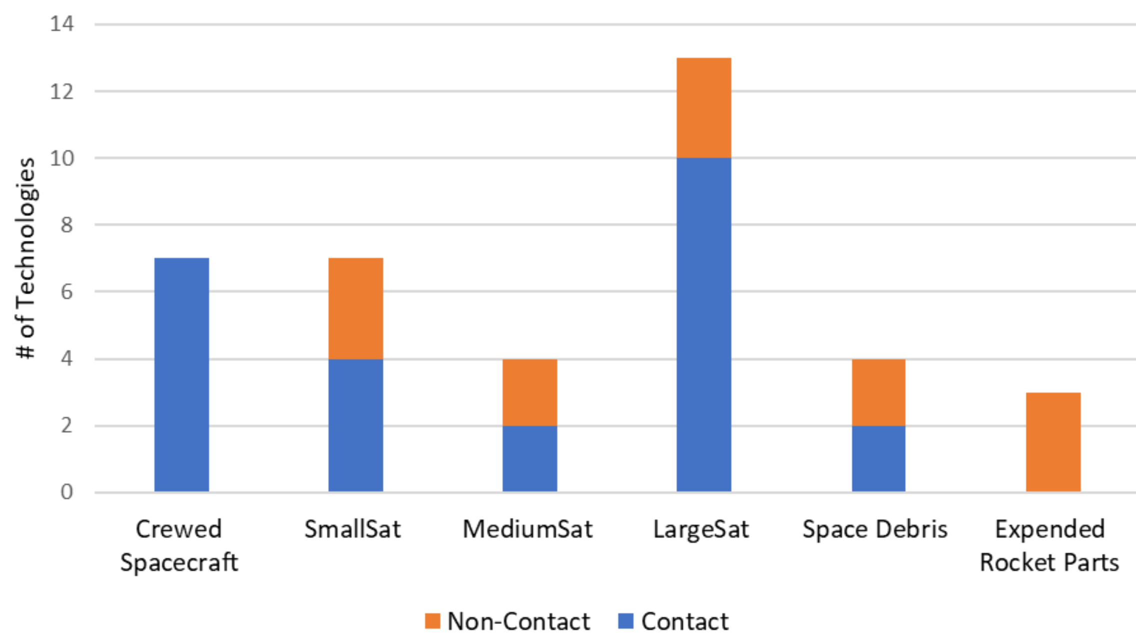

Figure 5: RPO, capture, docking, and mating technologies are useful for a wide range of client types. While most interest is focused on interaction with active satellites, this capability area is also used for managing expended components or space debris. LargeSat includes spacecraft over 1000 kg, MediumSat 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 decay or graveyard orbit, 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 vehicles to maintain orbit. The Space Shuttle was also responsible for many in space relocation activities, such as delivery of satellites to orbit or reorientation of satellites prior to deployment from the Space Shuttle cargo bay.

Relocation of space debris was first demonstrated on orbit in 2016 with China's Aolong-1 mission. Similar to Aolong-1, Astroscale's ELSA-d mission was focused on the relocation of end-of-life satellites from an active orbit to a graveyard orbit. 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 the development of space debris removal technologies, relocation technologies have also been advanced through docked life extension missions. Northrop Grumman's MEV spacecraft currently provides docked life extension services to commercial payloads. Planned mission extension spacecraft include Northrop Grumman's MEP and Starfish Space's Otter. These docked, life-extension servicing spacecraft are ideal in situations where a client space object 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, docked, life-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 life-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 have the capability to perform large orbital changes, and rideshare upper stages, which can deliver 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. As shown in the figure, 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 and into xGEO or cislunar orbits.

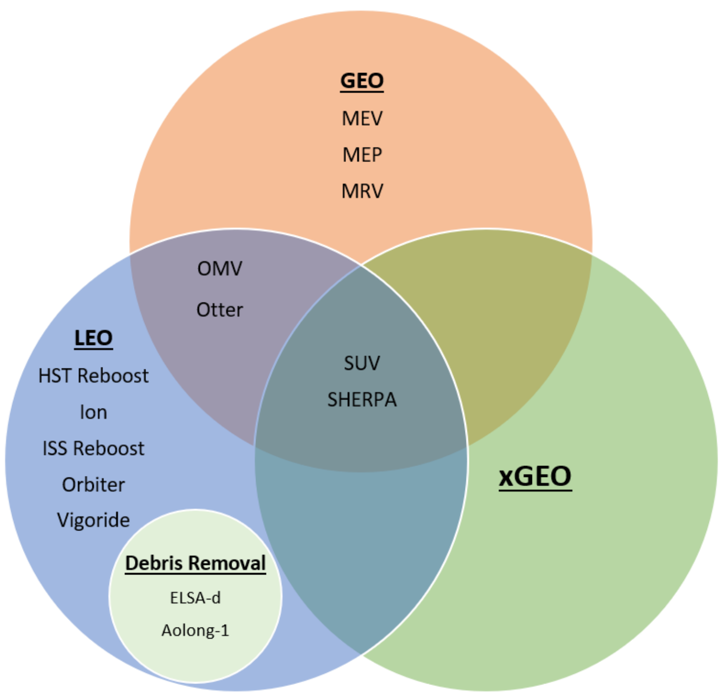

Figure 6: Relocation capabilities are currently heavily focused on LEO and GEO orbital regimes, and on commercial spacecraft targets. Of the technologies included in this figure, Aolong-1, ELSA-d, HST reboost, Ion, ISS reboost, MEV, and SHERPA have been demonstrated on orbit. Progress has been made towards 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 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 servicing spacecraft 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 spacecraft. Several developers have previously created purpose-built modular interfaces and servicing aids to perform ISAM functions to a spacecraft. The current 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 been demonstrated in space, such as interfaces between elements of the ISS. These interfaces enabled the modular assembly and servicing of the research platform and demonstrated key IVR and power supply capabilities. Furthermore, external payload platforms on the ISS (e.g., ELC, 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 prepared for servicing operations during design, was serviced five times by astronauts aboard the Space Shuttle. Other examples of interfaces and modular spacecraft that have flown in space include Altius's Dog Tag mechanical interface, which flies on OneWeb satellites; Novawurks's SLEGO interface and modules, which can provide mechanical attachment and transfer data, power, and fluids between modules and payloads; and ROSA, which were first deployed on the ISS in 2017. 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. In 2021, GITAI's S1 robotic arm demonstrated autonomous and teleoperated standard IVA tasks onboard the ISS within the Nanoracks Bishop Airlock pressurized volume. During the demonstration, the S1 completed standard taskboard interactions, including cable and switch actuation.

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.

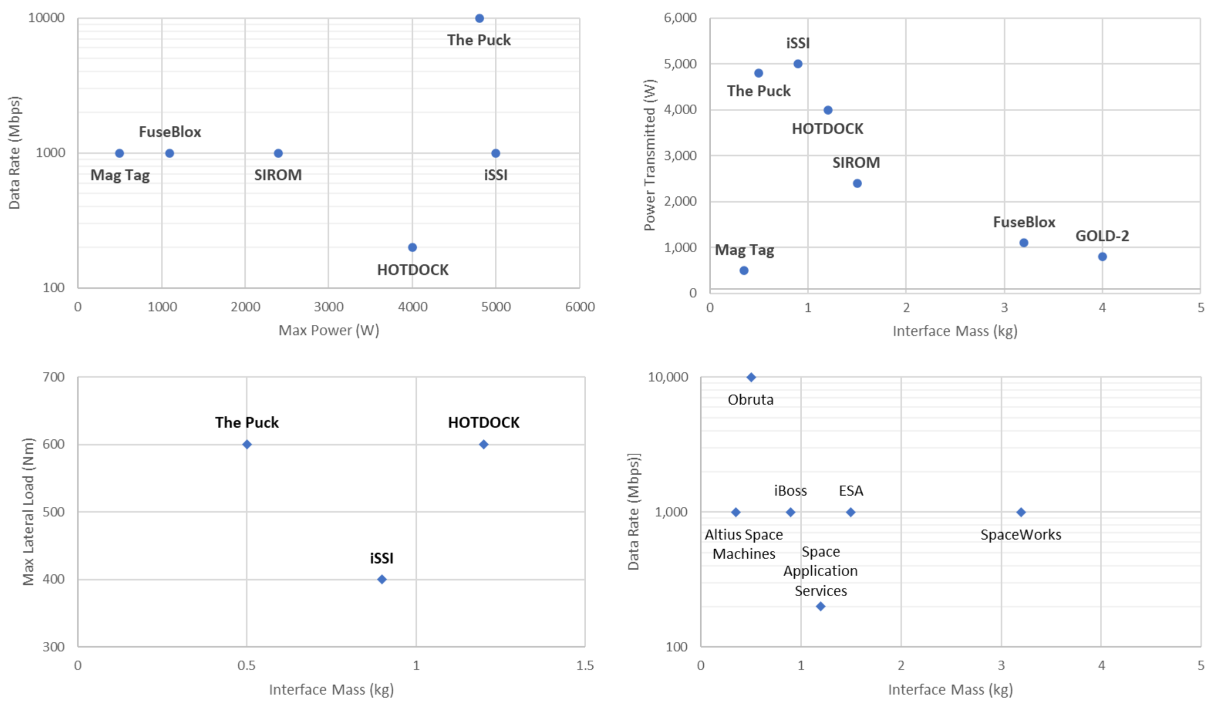

Figure 7: Modular interfaces are being developed to support multiple types of spacecraft to create an ISAM ecosystem where client satellites and ISAM servicing agents can readily create mechanical, fluid, power, data, and thermal connections. This figure presents some of the interfaces in use and under 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 unprepared spacecraft. While Landsat 7 was not prepared for servicing operations to occur 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, which is a complexity that would not be required if the client was designed to accept propellant on orbit.

NASA's OSAM-1 and DARPA's RSGS are currently planned key government flight demonstration missions 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.

Between 2012 to 2015, the RRM-1 and -2 payloads on the ISS used Dextre and custom robotic tooling to demonstrate the capability to interface with legacy spacecraft components that were not prepared for in-space servicing for the purpose of engaging, manipulating, and releasing.

3.6 Refueling and Fluid Transfer

Refueling and Fluid Transfer is the capability to move fluid between spacecraft. 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.

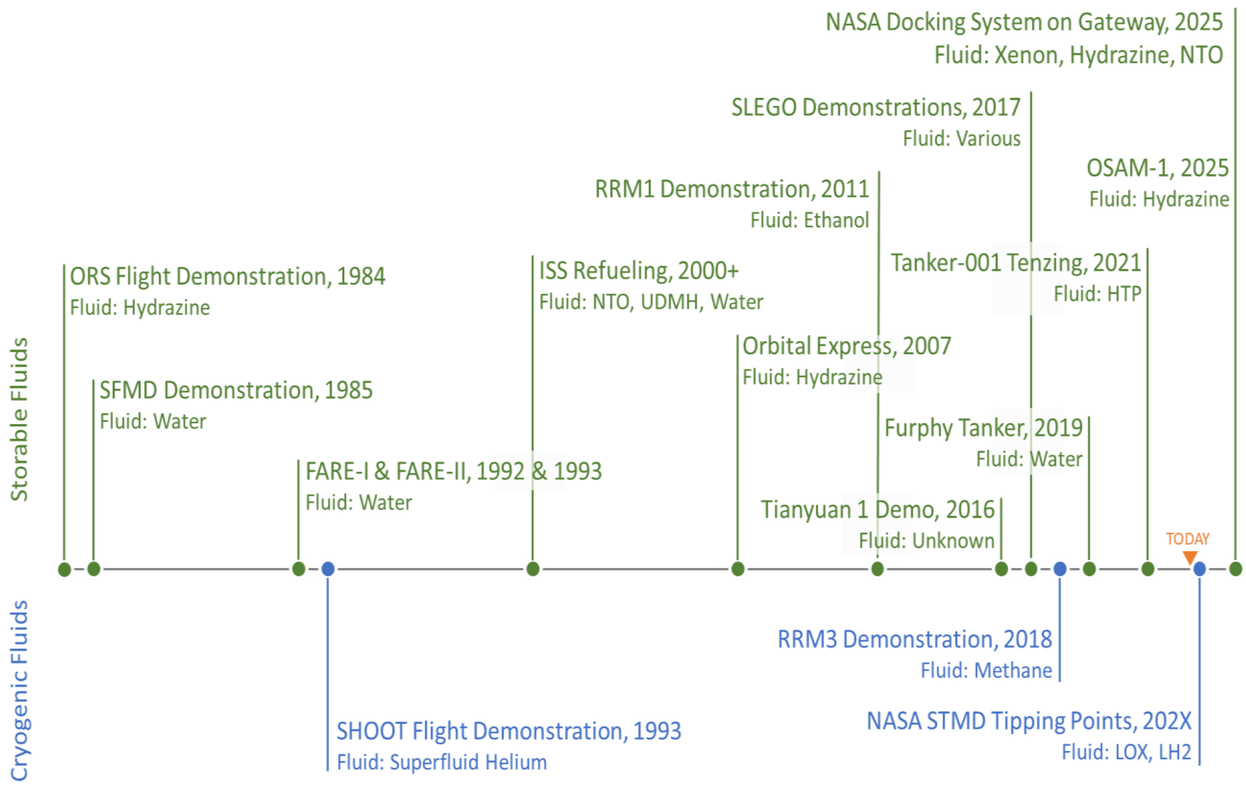

Figure 8: Storable fluid transfer has been demonstrated many times, including in operational missions like the ISS. The future is heading toward commercial refueling services (especially for storable fluids) and demonstrations are planned to test large-scale cryogenic fluid transfer in space.

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 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, because future missions will rely on cryogenic propellants, multiple flight demonstrations are currently 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 using robotics and human construction. Construction of the ISS began in November of 1998 and the first resident crew arrived in November of 2000. Multiple 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. EBW 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.

Through hosted experiments on the ISS, the RRM-1, -2, and -3 payloads demonstrated the capability to stow and retrieve tools to and from on-orbit protective enclosures (RRM payloads and the RiTS). In addition, the ORU/Tool Changeout Mechanisms were 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. Through another hosted experiment opportunity on the ISS in 2021, GITAI's S2 robotic arm demonstrated the assembly of a four-panel solar array within the Nanoracks Bishop Airlock pressurized volume.

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. The OSAM-2 mission plans to demonstrate the ability to 3D print structural beams using the ESAMM subsystem developed by Redwire.

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.

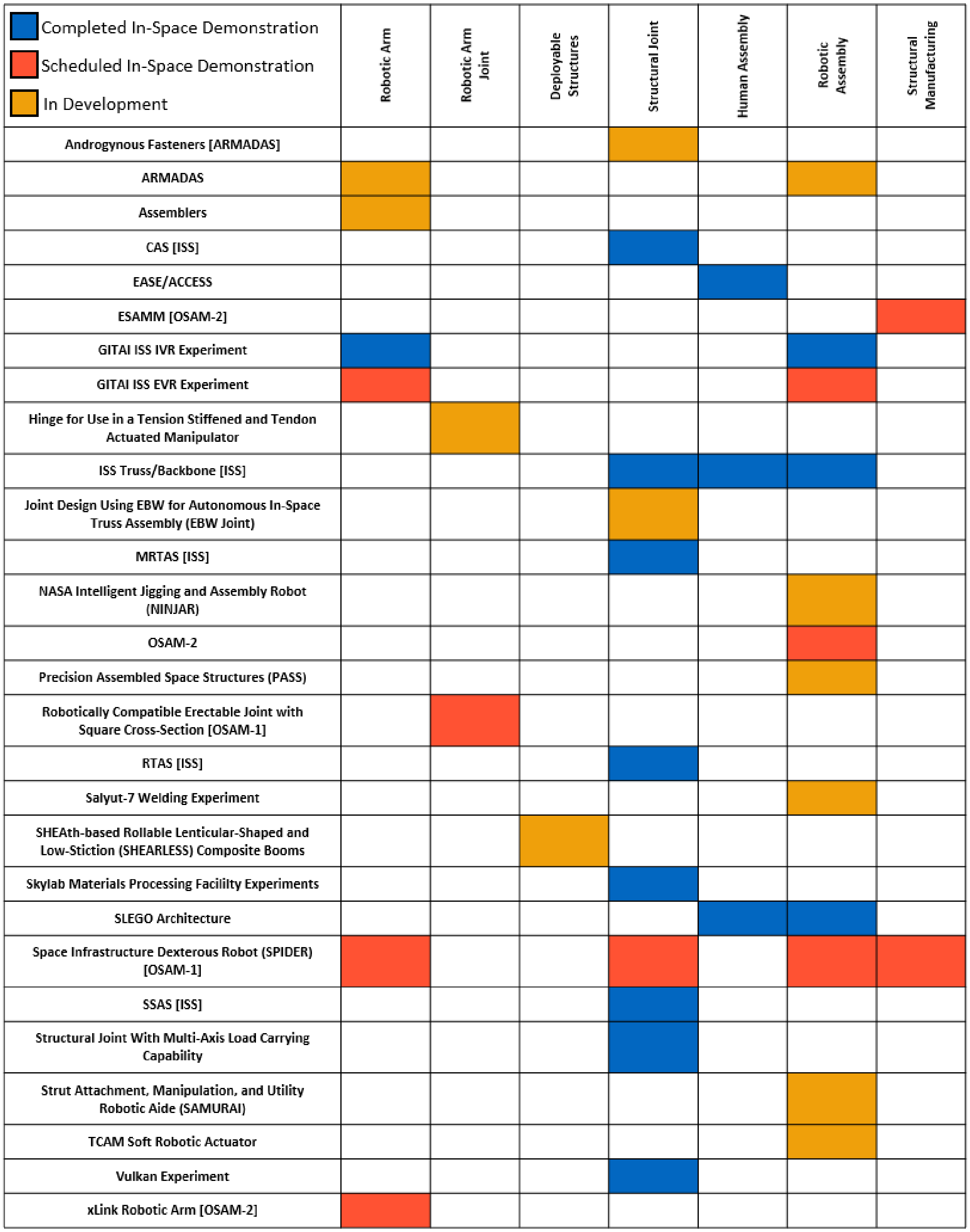

Figure 9: The technologies which contribute to the capability of structural manufacturing and assembly are wide ranging, due to the complexity of the process. The current advancement in this capability area focuses on robotic structural manufacturing and assembly.

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, reuse, and repurposing results in reduced strain on the space logistics supply chain and reframes spacecraft components and materials as part of the "native" resources available for sustained presence in space.

The first polymer recycling facility, 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 on an as-needed basis and then recycled for use later in the mission, reducing the need for transportation of single-use parts or an excess of stock materials to the ISS.

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. A major benefit of parts and goods manufacturing in-space is the ability to quickly produce a component when needed, thus reducing the timeline for delivery and quantity of launched spare components. 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 an FDM 3D printer developed by Made In Space, now a Redwire company, and operated in a MSG. Made In Space next developed the AMF, which was sent to the ISS in 2016 and remains a current installation. Both 3D printers which operated on the ISS printed 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. 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. 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. Figure 10 provides an overview of demonstrated and in-development technologies in this capability area.

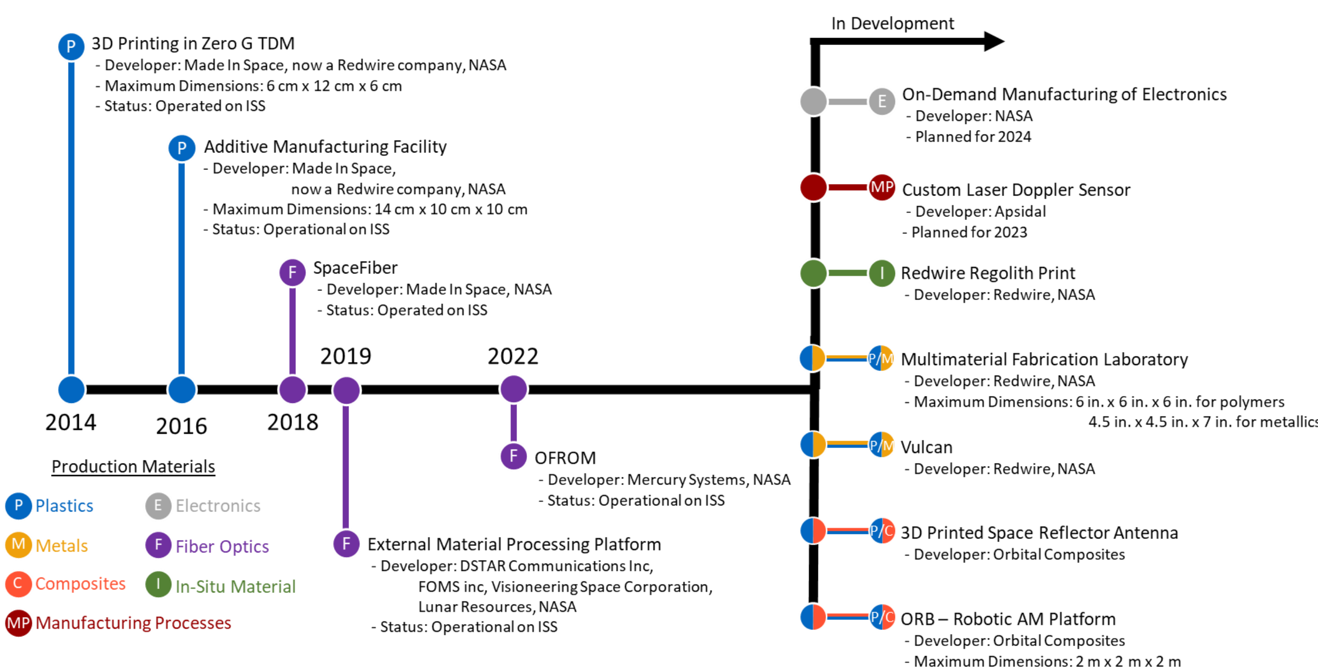

Figure 10: The first demonstrations of parts and goods manufacturing in space began in 2014 with the use of 3D printed plastics. Current production techniques in development aim to expand the production capabilities to metals, electronics, and even ISRU-regolith infused feedstock.

3.10 Surface Construction

Surface Construction involves excavating, constructing, assembling, and outfitting structures and infrastructure on a non-terrestrial 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 will likely be Earth-sourced, lunar regolith is expected to be a key source of future building material.

Projects such as GaLORE have been exploring concepts for extraction of raw materials from lunar regolith. Through the GaLORE project, lunar regolith will be heated until it is reduced to a molten state. By 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. This type of blended feedstock is the basis for construction under the Redwire Regolith Print project. 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 use of this regolith material for construction has been explored through several NASA projects, including the 3D Printed Habitat Challenge, the ACME project, CHAPEA, the ISFR project, and MMPACT.

Surface construction operations can also be further subdivided into remote and autonomous operations. The initial stages of excavation and construction are expected to be performed primarily via teleoperated platforms such as bulldozers, diggers, and cranes designed for operation in a low-gravity environment. The LANCE and RASSOR projects are both developing excavation capabilities, with LANCE developing a lightweight bulldozer blade and RASSOR developing an innovative regolith excavation platform.

Once the preliminary work is far enough along, autonomous systems are likely to handle tasks such as processing the extracted regolith material and assembly of simple structures, though the plans for such systems are still in very early stages. Concepts for manipulation though autonomous systems include the GITAI R1, a rover which was tested in a lunar simulant environment in 2023, and LSMS, a scalable, tendon actuated crane system with over 12 years of design heritage. Figure 11 shows a condensed sequence of the technology from excavation to processing to construction.

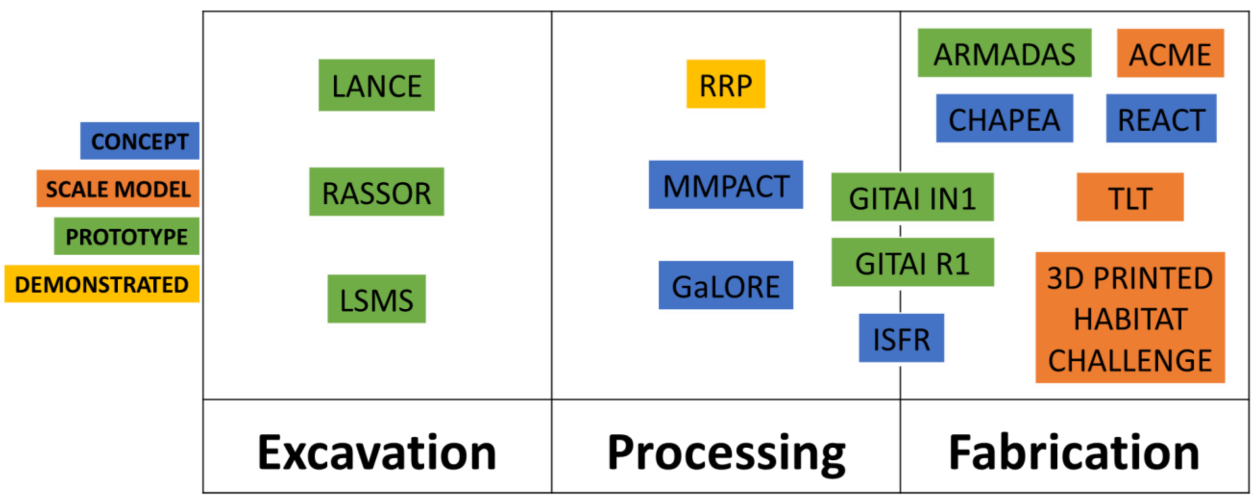

Figure 11: Surface Construction technologies, sorted into three main categories. Regolith excavation is the easiest category to simulate on Earth, reflected by it having the most advanced readiness level.

3.11 Inspection and Metrology

Inspection and Metrology involve the observation of in-space systems 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, or 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 provide information to determine 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 and send the collected data to Earth for off-board analysis.

Inspection is often carried out via high-definition cameras processing standard visual images, although other sensors, such as ultrasound or multispectral sensors, are also implemented depending on the mission. The sensors are deployed from a variety of platforms, such as anchored to a structure or robotic arm or free flying on a dedicated satellite vehicle.

Anchored inspection payloads have been prevalent tenants of the ISS, which has historically provided a platform for technology demonstration and often employs inspection techniques for safe operation. Inspection payloads hosted on the ISS include NASA's VIPIR, RELL, and the bio-memetic snake arm robot. 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 Earth-based robotic operators. RELL is a robotic tool used along with the SSRMS to scan (inspect) various areas of the ISS for signs of pressure increases indicative of ammonia leakage. This versatile tool has an integral mass spectrometer used to differentiate molecules within a pressure source and an ion gauge used as a general pressure gauge. The RELL tool can be used to support additional 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 the ISS and conduct inspection and repairs in areas that would be difficult for a human to access.

Free-flying inspection payloads have been under development since the deployment of the XSS satellites launched in 2003 and 2005. The AFRL XSS satellites were designed without a permanent target, instead performing proximity inspections on dead or inactive space objects near each satellite's orbit. Free-flying inspection satellites have since flown through the ANGELS and AeroCube satellites. ANGELS, also developed by AFRL, evaluated situational awareness techniques around a Delta-IV upper stage while 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. Figure 12 classifies the inspection platforms according to their mission types.

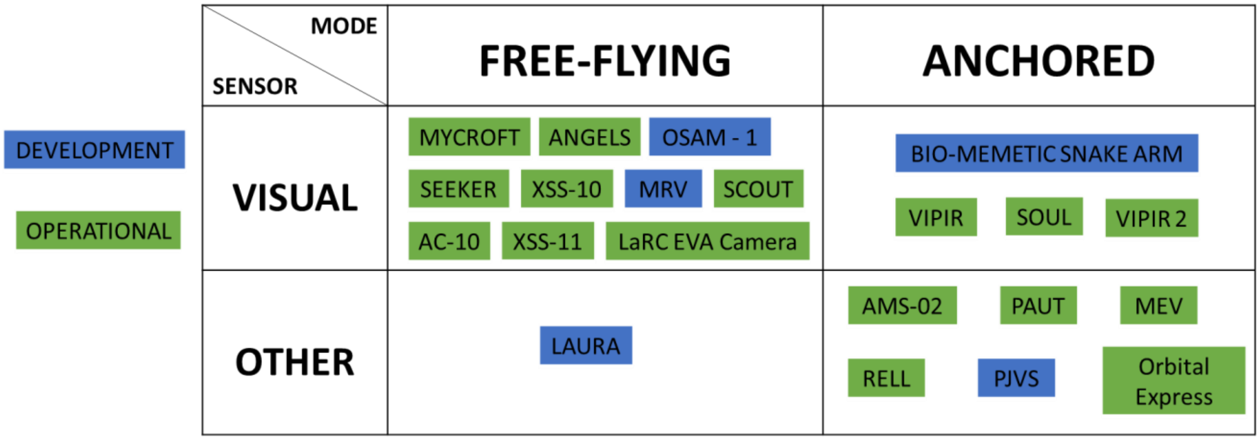

Figure 12: Inspection and metrology technologies, sorted into four main categories. Free-flying visual platforms command by far the highest in-demand application of this technology area.

4 ISAM Developers and Facilities

The previously discussed ISAM capability areas and corresponding entries are supported by a thriving and expanding community of developers from government, commercial, and academic sectors. The 88 cataloged ISAM developers range in size from government agencies to corporations of fewer than 10 employees and represent 13 countries around the world. More information on each of these developers can be found in Section 8. Figure 13 shows the number of ISAM developments by distinct associations.

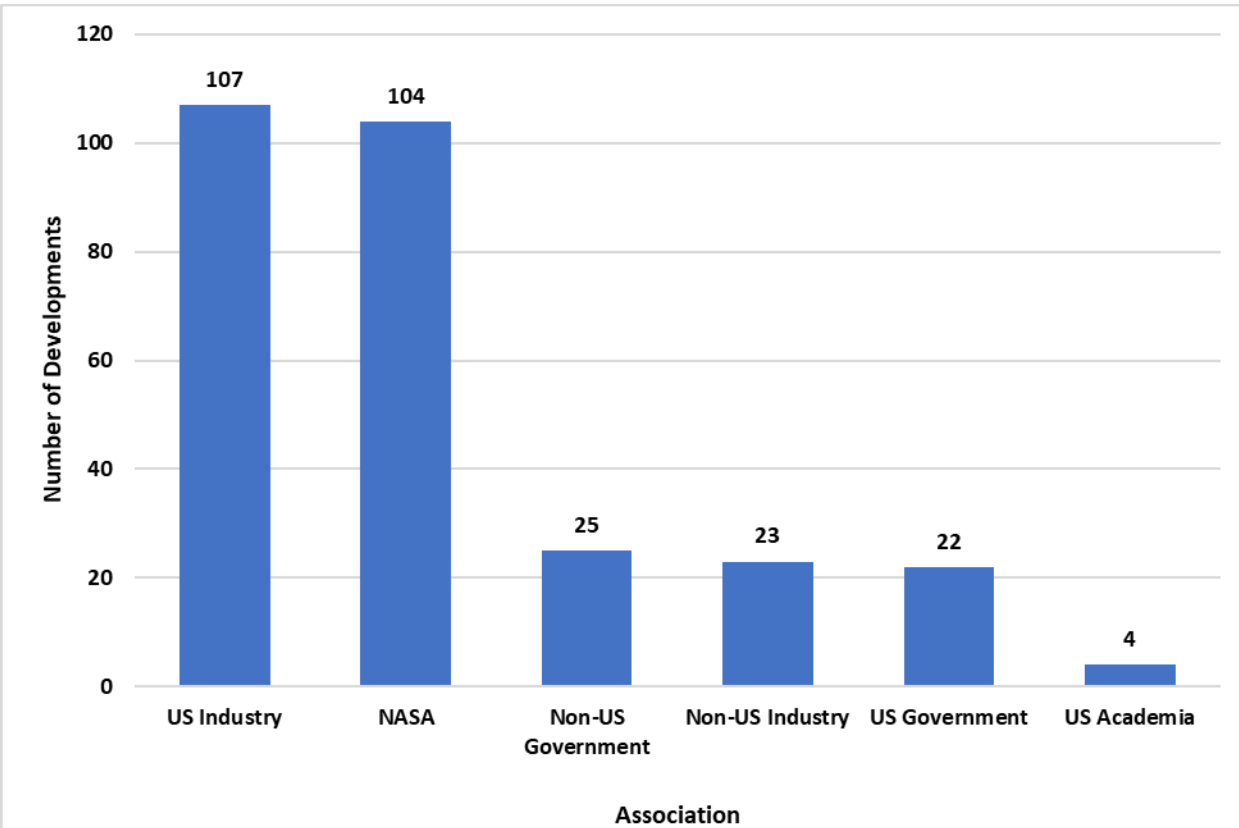

Figure 13: Number of developments by developer association. Each of the developers catalogued was organized by association, as shown above*. The number of developments represents the sum of all capability area activities completed by the developers within that association.*

Facilities provide an important resource in advancing ISAM capabilities. Figure 14 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. A collection of ISAM facilities is further detailed in Section 9.

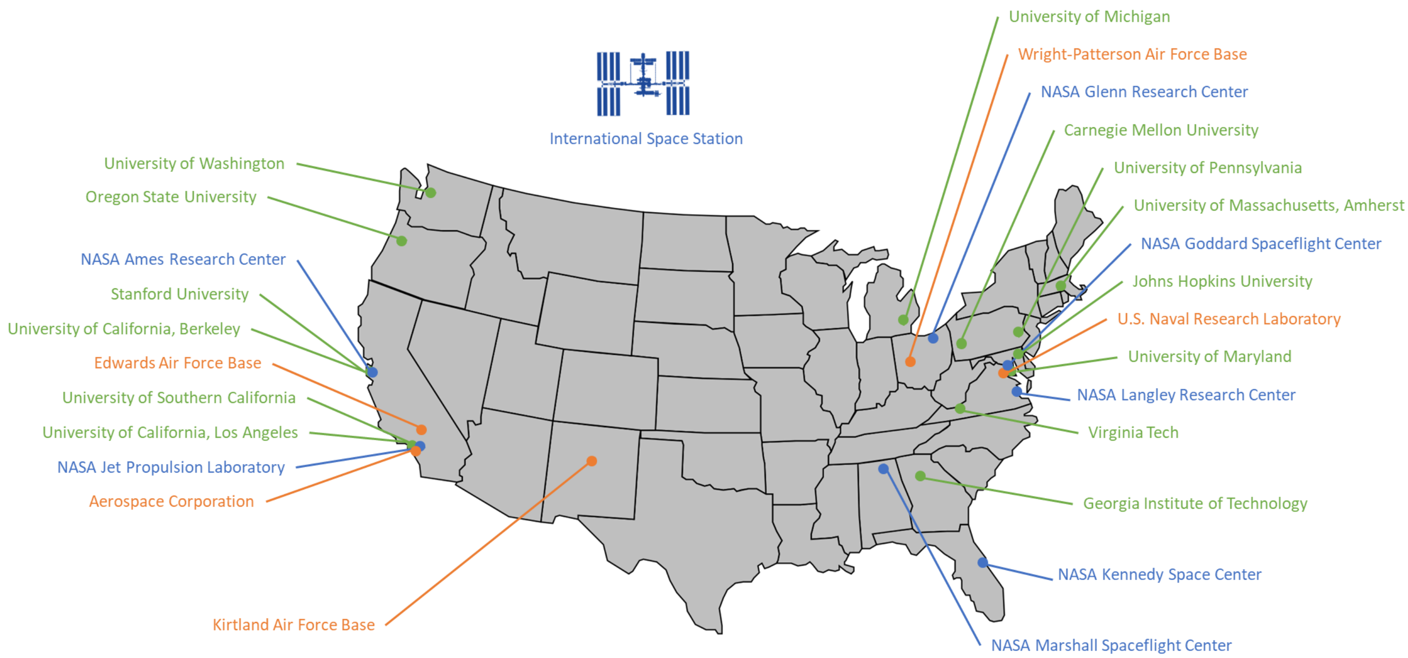

Figure 14: Facilities that have been advancing ISAM capabilities exist across the country and in space aboard the ISS. This figure presents a summary of the facilities captured in this document, with Department of Defense and supporting FFRDC facilities in orange, NASA facilities in blue, and academic facilities in green. More information on each facility is in Section 8.

5 KEY ISAM MISSIONS

Several of the ISAM activities and technologies included in this document contribute to larger missions, programs, or projects. These higher-level activities, which are discussed in Section 2 and displayed in Figure 1, have led the space industry in ISAM technology development and have highlighted the utility of these technologies. Due to their historical significance, technical advancement, and reach into several capability areas, these missions have been designated as "Key ISAM Missions". Descriptions of these missions are as follows:

- ETS-VII: ETS-VII (or Kiku7) was a JAXA (formerly NASDA) technology demonstration satellite which performed space robotic experiments and demonstrated its utility for uncrewed orbital operation and servicing tasks. The satellite completed operation in 1998.

- HST: launched in 1990, the HST is an optical space telescope positioned in low Earth orbit. To maintain operations, the HST was serviced by shuttle crews on multiple occasions, in both planned and unplanned servicing missions. After initial launch, the HST was retrofitted with additional ORU Swap capabilities to ease future servicing missions.

- ISM: the NASA ISM Project incorporates a portfolio of technologies focused on in-space on-demand fabrication, repair, and recycling capabilities. The Project adapts terrestrial developed manufacturing technologies to in-space environments, often demonstrated on the ISS. ISM projects offer the ability to reduce costs through minimizing launch mass and reduce risk through less reliance on spares and overdesign for reliability.

- ISS: the ISS is a crewed space laboratory in Earth's low earth orbit. During the ISS assembly process, which began in 1998, many in-space assembly, RPO, and docking technologies were required to piece together the modular structure. The ISS is host to many ISAM related technology demonstrations.

- MEV: Developed by Northrop Grumman, 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.

- Orbital Express: Launched March 8, 2007, as part of the United States Air Force 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 ORU transfer and installation.

- OSAM-1: 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 on orbit.

- OSAM-2: The technology demonstration, previously called Archinaut One and now OSAM-2, plans to 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.

- RRM: the RRM missions are a set of three servicing and refueling technology demonstration missions which were hosted by the ISS and completed in 2011, 2015, and 2018. The focus of RRM1 was servicing of heritage spacecraft without standard interfaces. RRM2 demonstrated use of new inspection and manipulation tools for servicing and refuel. RRM3 focused on cryogenic propellant storage, gauging, and transfer. Each of these missions were developed through the NExIS projects division of NASA GSFC.

- RSGS: the DARPA RSGS program will demonstrate robotic servicing within GEO through use of a RSV. The commercially owned and operated RSV will be comprised of a DARPA-developed toolkit and a privately developed spacecraft. The RSGS program intents to demonstrate robotic servicing, on-orbit mission flexibility, and commercial and government collaboration through a multi-year, multi-mission campaign.

Table 1 details the ISAM activities which support each milestone mission and the linkage to the capability area(s) applicable to those activities.

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	ARMADAS	7, 10
	Androgynous Fasteners [ARMADAS]	7
	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
	Additive Manufacturing Facility (AMF) [ISM]	9
	Custom Laser Doppler Sensor	9
	External Material Processing Platform	9
	Made in Space: SpaceFiber	9
	Metal Advanced Manufacturing Bot-Assisted Assembly (MAMBA)	8
	Multimaterial Fabrication Laboratory [ISM]	9
	On-Demand Manufacturing of Electronics (ODME) [ISM]	9
	Orbital Fiber Optic Production Module (ORFOM)	9
	Recyclable Packaging Materials	8
	Redwire Regolith Print (RegISS) [ISM]	9, 10
	ReFabricator [ISS]	8
	Sintered Inductive Metal Printer with Laser Exposure (SIMPLE) [ISM]	9
	Vulcan [ISM]	9

Mission	Activity	Area
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, 6
	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
	Roll-Out Solar Array (ROSA)	4
	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
OSAM-1	OSAM-1	2, 5, 6, 11
	NASA Servicing Arm [OSAM-1]	1
	Robotically Compatible Erectable Joint with Square Cross-Section [OSAM-1]	7
	Space Infrastructure Dexterous Robot (SPIDER) [OSAM-1]	1, 7

Mission	Activity	Area
OSAM-2	OSAM-2	7
	ESAMM	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
	Visual Inspection Poseable Invertebrate Robot 2 (VIPIR2) [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

6 Contributors

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7 Appendix – ISAM Activities

This appendix presents more details on the ISAM development activities and technologies that define the current state of ISAM. For the use of the tables found in this appendix, the capability areas are numbered from 1 to 11, as follows:

1. Robotic Manipulation (RM)
2. RPO, Capture, Docking, and Mating (RCDM)
3. Relocation (R)
4. Planned Repair, Upgrade, Maintenance, and Installation (PRUMI)
5. Unplanned or Legacy Repair and Maintenance (ULRM)
6. Refueling and Fluid Transfer (RFT)
7. Structural Manufacturing and Assembly (SMA)
8. Recycling, Reuse, and Repurposing (RRR)
9. Parts and Goods Manufacturing (PGM)
10. Surface Construction (SC)
11. Inspection and Metrology (IM)

In addition to the 11 core capability areas, a series of "cross-cutting" capability areas have been identified as the hardware, software, services, and regulations which serve to support those core areas. Incorporation of entries for these cross-cutting capability areas is expected in subsequent editions of this document. The identified cross-cutting capability areas include:

12. Software and Algorithms
13. Management, Logistics, and Analysis
14. Policy, Standards, and Certification
15. Systems, Electronics and Computers
16. Guidance, Navigation and Control

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 detailed in multiple capability areas due to the broad scope or impact of an activity. 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		
ADRAS-J		RCDM01									
AeroCube-10		RCDM02									
AeroCube-10 (AC-10)											IM01
Alpha Magnetic Spectrometer (AMS-02) [ISS]											IM02
Androgynous Fasteners [ARMADAS]							SMA01				
ANGELS		RCDM03									
Aolong-1		RCDM04	R01								
APAS [ISS]		RCDM05									
Argon Autonomous Rendezvous and Docking (AR&D) Sensor		RCDM06									
ARMADAS							SMA02			SC03	
Assemblers	RM01						SMA03				
ASTP-DM		RCDM07									
Automated Navigation and Guidance Experiment for Local Space (ANGELS)											IM03
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	

Activity	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**
Cooperative Service Valve (CSV)						RFT01					
COSMIC		RCDM08									
Cryogenic Servicing Tool (CST) [RRM]						RFT02					
Custom Laser Doppler Sensor									PGM04		
Dextre [ISS]	RM05										
Dog Tag				PRUMI02							
EASE/ACCESS							SMA05				
ELSA-d		RCDM09	R02								
ELSA-M		RCDM10									
Engineering Test Satellite VII (ETS-VII)	RM06	RCDM11									
ESAMM							SMA06				
European Robotic Arm (ERA) [ISS]	RM07										
External Material Processing Platform									PGM05		
Fluid Acquisition & Resupply Experiment I (FARE-I)						RFT03					
Fluid Acquisition & Resupply Experiment II (FARE-II)						RFT04					
Front-end Robotic Enabling Near-term Demonstration (FREND) [RSGS]	RM08										
Furphy Prototype Tanker [ISS]						RFT05					
FuseBlox				PRUMI03							
GaLORE Project										SC05	
GOLD-2 Connector [ISS]				PRUMI04							
HelioSwarm		RCDM12									
Hinge for Use in a Tension Stiffened and Tendon Actuated Manipulator							SMA07				
HOTDOCK				PRUMI05							
iBOSS iSSI				PRUMI06							
IN1	RM09										
In-Situ Construction GCD Project										SC06	
In-Situ Fabrication and Repair Project (ISFR)										SC07	
Instrument Deployment Arm (Insight)	RM10										
International Berthing and Docking Mechanism (IBDM) [ISS]		RCDM13									
International Space Station Truss/Backbone [ISS]							SMA08				

Activity	1	2	3	4	5	6	7	8	9	10	11
ION Satellite Carrier			R03								
ISS EVR Experiment				PRUMI07			SMA09				
ISS IVR Experiment				PRUMI08			SMA10				
ISS Reboost			R04								
Japanese Experiment Module Remote Manipulator System (JEM-RMS) [ISS]	RM11										
Japanese Experiment Module Small Fine Arm [ISS]	RM12										
Joint Design Using Electron Beam Welding for Autonomous In-Space Truss Assembly (EBW Joint)							SMA11				
KRAKEN [ISS]	RM13										
LANCE										SC08	
Laura											IM05
LEO Knight		RCDM14			ULRM01						
Lightweight Surface Manipulator System (LSMS)	RM14									SC09	
Made in Space: SpaceFiber									PGM06		
Mag Tag				PRUMI09							
MakerSat [OSAM-1]							SMA12				
Mars Exploration Rover Robotic Arm	RM15										
Mars Science Laboratory Robotic Arm	RM16										
Mars Surveyor 2001 Robotic Arm	RM17										
Mars Volatiles and Climate Surveyor Robotic Arm (MVACS)	RM18										
Metal Advanced Manufacturing Bot-Assisted Assembly (MAMBA)								RRR01			
Mission Extension Pods (MEP)			R05		ULRM02						
Mission Extension Vehicle (MEV)		RCDM15	R06								IM06
Mission Robotic Vehicle (MRV) [RSGS]		RCDM16	R07		ULRM03						IM07
MMPACT										SC10	
Mobile Metamaterial Internal Co-Integrator (MMIC-I) [ARMADAS]	RM19										
MRTAS [ISS]							SMA13				
Multifunction Tool [RRM]						RFT06					
Multi-Function Tool 2 (MFT2) [RRM]						RFT07					

Activity	1	2	3	4	5	6	7	8	9	10	11
Multimaterial Fabrication Laboratory [ISM]									PGM07		
Mycroft		RCDM17									IM08
NASA Docking System (NDS)[ISS]		RCDM18				RFT08					
NASA Intelligent Jigging and Assembly Robot (NINJAR)							SMA14				
NASA Langley’s Extravehicular Activity (EVA) Infrared Camera											IM09
NASA Servicing Arm [OSAM-1]	RM20										
NASA STMD 2020 Tipping Point Selections on Cryogenic Fluid Management Technology Demonstration						RFT09					
Nautilus		RCDM19									
Nozzle Tool [RRM]						RFT10					
On-Demand Manufacturing of Electronics (ODME) [ISM]									PGM08		
ORB – Robotic AM Platform									PGM09		
Orbital Express		RCDM20		PRUMI10		RFT11					IM10
Orbital Express Demonstration Manipulator System (OEDMS) [Orbital Express]	RM21										
Orbital Fiber Optic Production Module (ORFOM)									PGM10		
Orbital Maneuvering Vehicle (OMV)			R08								
Orbital Refueling System (ORS) Flight Demonstration						RFT12					
Orbiter			R09								
OSAM-1		RCDM21			ULRM04	RFT13					IM11
OSAM-2							SMA15				
Otter		RCDM22	R10								
Otter Pup		RCDM23									
Perseverance Sample Handling Assembly (SHA)	RM22										
Phoenix Mars Lander Robotic Arm	RM23										
PMA [ISS]		RCDM24									
Precision Assembled Space Structures (PASS)							SMA16				
Programmable Josephson Voltage Standard (PJVS)											IM12
Progress Vehicle and ATV Refueling of ISS [ISS]						RFT14					

Activity	1	2	3	4	5	6	7	8	9	10	11
R1										SC11	
Ranger	RM24										
RASSOR										SC12	
RAVEN [ISS]		RCDM25									
REACT										SC13	
Recyclable Packaging Materials								RRR02			
Redwire Regolith Print (RegISS) [ISM]									PGM11	SC14	
ReFabricator [ISS]								RRR03			
Rendezvous, Proximity Operations, and Docking (RPOD) Kit				PRUMI11							
Robonaut2 [ISS]	RM25										
Robotic External Leak Locator (RELL) [ISS]											IM13
Robotic Refueling Mission 1 (RRM1)						RFT15					
Robotic Refueling Mission 2 (RRM2)					ULRM05						
Robotic Refueling Mission 3 (RRM3)						RFT16					
Robotically Compatible Erectable Joint with Square Cross-Section [OSAM-1]							SMA17				
Roll-Out Solar Array (ROSA)				PRUMI12							
RTAS [ISS]							SMA18				
S1	RM26										
S10	RM27										
S2	RM28										
Safety Cap Tool [RRM]						RFT17					
Salyut-7 Welding Experiment							SMA19				
Scaling Omnidirectional Lattice Locomoting Explorer (SOLL-E) [ARMADAS]	RM29										
SCOUT											IM14
SCOUT-Vision		RCDM26									
Seeker [ISS]											IM15
Servicing Mission 1 (STS-61) [HST]		RCDM27	R11	PRUMI13							
Servicing Mission 2 (STS-82) [HST]		RCDM28	R12	PRUMI14	ULRM06						
Servicing Mission 3A (STS-103) [HST]		RCDM29		PRUMI15							

Activity	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**
Servicing Mission 3B (STS-109) [HST]		RCDM30	R13	PRUMI16							
Servicing Mission 4 (STS-125) [HST]		RCDM31		PRUMI17	ULRM07						
SHEAth-based Rollable Lenticular-Shaped and Low-Stiction (SHEARLESS) Composite Booms							SMA20				
Sherpa			R14								
Shijian-17		RCDM32									
Sintered Inductive Metal Printer with Laser Exposure (SIMPLE) [ISM]									PGM12		
Skylab Materials Processing Facility Experiments							SMA21				
SLEGO Architecture				PRUMI18		RFT18	SMA22				
Sonatest Veo PAUT [ISS]											IM16
SOUL		RCDM33		PRUMI19							IM17
Space Infrastructure Dexterous Robot (SPIDER) [OSAM-1]	RM30						SMA23				
Space Utility Vehicle (SUV)			R15								
SSAS [ISS]							SMA24				
SSVP		RCDM34									
STAARK	RM31										
Standard Interface for Robotic Manipulation of Payloads in Future Space Missions (SIROM)				PRUMI20							
Storage Fluid Management Demonstration (SFMD)						RFT19					
Strela Cargo Cranes [ISS]	RM32										
Structural Joint With Multi-Axis Load Carrying Capability							SMA25				
Strut Attachment, Manipulation, and Utility Robotic Aide (SAMURAI)							SMA26				
Superfluid Helium On-Orbit Transfer (SHOOT) Flight Demonstration						RFT20					
Tailored Universal Feedstock for Forming (TuFF) Reformability Demo								RRR04			
TALISMAN	RM33										
Tall Lunar Tower (TLT)										SC15	
Tanker-001 Tenzing		RCDM35				RFT21					

Activity	1	2	3	4	5	6	7	8	9	10	11
TCAM Soft Robotic Actuator							SMA27				
Thermally Reversible Polymers for AM Feedstock								RRR05			
Tianyuan 1 refueling demonstration						RFT22					
Vigoride			R16								
Visual Inspection Poseable Invertebrate Robot (VIPIR) [RRM]											IM18
Visual Inspection Poseable Invertebrate Robot 2 (VIPIR2) [RRM]											IM19
Vulcan [ISM]									PGM13		
Vulkan Experiment							SMA28				
Wire Cutter Tool [RRM]					ULRM08						
xLink Robotic Arm [OSAM-2]	RM34						SMA29				
XSS-10		RCDM36									IM20
XSS-11		RCDM37									IM21

7.1 Robotic Manipulation

7.1.1 RM01: Assemblers

Description: Assemblers is a technology development for a modular robotic manipulator that consists of a variable number of stacked Stewart platforms. The goal of this project is to increase the technology readiness level for modular robots and autonomous in-space assembly and to develop a robotic prototype for ground testing. Both new hardware and software is being developed.
Developer(s): NASA Langley Research Center (LaRC)
Country: United States
First Use Date: TBD
Status: In Development
Reach (m): 1.01
Degrees of Freedom: Unavailable
Grapple Type: Unavailable

7.1.2 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(s): Spar Aerospace
Country: Canada
First Use Date: 1981
Status: Completed
Reach (m): 15
Degrees of Freedom: 8
Grapple Type: Snare End Effector

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

Description: Officially known as the Space Station Remote Manipulator System (SSRMS), Canadarm2 supports a wide array of ISS operations. 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(s): Canadian Space Agency (CSA), MDA Space
Country: Canada
First Use Date: 2001
Status: Operational
Reach (m): 17.6
Degrees of Freedom: 7
Grapple Type: Snare End Effector, Latches, Umbilicals

7.1.4 RM04: Canadarm3

Description: The Canadarm3 is a robotic remote manipulator arm similar to the Space Shuttle Canadarm and International Space Station Canadarm2. Canadarm3 will be used for berthing the modules and inspecting the Lunar Gateway. 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(s): Canadian Space Agency (CSA), MDA Space
Country: Canada
First Use Date: Scheduled for 2024
Status: In Development
Reach (m): 8.5
Degrees of Freedom: 7
Grapple Type: Unavailable

7.1.5 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) previously 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(s): Canadian Space Agency (CSA), MDA Space
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

7.1.6 RM06: Engineering Test Satellite VII (ETS-VII)

Description: ETS-VII (Japanese nickname: Kiku7) was a NASDA (which is now part of JAXA) technology demonstration satellite. The overall mission objectives are to conduct space robotic experiments with an onboard 2-meter arm and to demonstrate its utility for uncrewed orbital operation and servicing tasks (e.g., rendezvous-docking techniques).
Developer(s): National Space Development Agency of Japan (NASDA)
Country: Japan
First Use Date: 1998
Status: Completed
Reach (m): 2
Degrees of Freedom: 6
Grapple Type: Grapple

7.1.7 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(s): Airbus Defence and Space Netherlands (ADSN)
Country: European Union
First Use Date: 2021
Status: Operational
Reach (m): 11.3
Degrees of Freedom: 7
Grapple Type: Grapple Integrated Tools

7.1.8 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 and RSGS. The arm is driven by the MOOG Rikishi Electronics Unit, which is designed to drive up to nine separate robotic arm joints.
Developer(s): Defense Advanced Research Projects Agency (DARPA), Naval Research Laboratory (NRL), MOOG

Country: United States
First Use Date: 2007
Status: Completed
Reach (m): 1.8
Degrees of Freedom: 7
Grapple Type: Grapple

7.1.9 RM09: IN1

Description: The IN1, in development by Japanese startup GITAI, is an inchworm-type robotic arm equipped with "grapple end-effectors" on both ends of the arm. This unique feature increases "Capability", which enables it to connect to various tools to perform multiple tasks, and "Mobility", which enables it to move in any direction. It can also connect/disconnect itself among different vehicles, such as rovers, landers, Lunar base, etc. In March 2023, a demonstration of cooperative lunar base construction using two GITAI inchworm-type robotic arms and two GITAI Lunar Robotic Rovers in a simulated lunar environment was successfully completed.
Developer(s): GITAI
Country: Japan
First Use Date: TBD
Status: In Development
Reach (m): 1.5
Degrees of Freedom: Unavailable
Grapple Type: Internal Proprietary Interface, Camera, Tool Change Capability

7.1.10 RM10: Instrument Deployment Arm (Insight)

Description: The Instrument Deployment Arm (IDA) originated as the robotic arm built for the Jet Propulsion Laboratory (JPL) for the cancelled Mars 2001 Surveyor mission in 1998. It was later used on the InSight Mars lander to deploy instruments on the surface and orient the deployment camera.
Developer(s): Maxar Technologies, MDA Space
Country: United States
First Use Date: 2018
Status: Operational
Reach (m): 1.9
Degrees of Freedom: 4
Grapple Type: Scoop, Grapple, Camera

7.1.11 RM11: Japanese Experiment Module Remote Manipulator System (JEM-RMS) [ISS]

Description: Kibo's robotic arm, Japanese Experiment Module Remote Manipulator System (JEM-RMS), 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(s): Japan Aerospace Exploration Agency (JAXA)

Country: Japan
First Use Date: 2008
Status: Operational
Reach (m): 10
Degrees of Freedom: 6
Grapple Type: Grapple, JEM SFA Connection

7.1.12 RM12: Japanese Experiment Module Small Fine Arm [ISS]

Description: The Small Fine Arm (SFA) consists of electronics, booms, joints, effectors called "tools", and cameras. The SFA attaches to the end of the JEM-RMS when operated.
Developer(s): Japan Aerospace Exploration Agency (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

7.1.13 RM13: KRAKEN [ISS]

Description: Tethers Unlimited Inc. 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(s): 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

7.1.14 RM14: 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 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(s): NASA Langley Research Center (LaRC)
Country: United States
First Use Date: TBD
Status: In Development

Reach (m): 7.5
Degrees of Freedom: 3
Grapple Type: Unavailable

7.1.15 RM15: 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(s): National Aeronautics and Space Administration (NASA), Maxar Technologies, MDA Space
Country: United States
First Use Date: 2004
Status: Completed
Reach (m): 1
Degrees of Freedom: 5
Grapple Type: Abrasion Tool, Spectrometer, Camera

7.1.16 RM16: Mars Science Laboratory Robotic Arm

Description: The Mars Science Laboratory (also known as Curiosity) mission incorporates many lessons learned from the Pathfinder mission and Sojourner rover, the Mars Exploration Rovers, and the Phoenix Lander to explore Mars and help understand if it ever had the conditions to support life. Curiosity's robotic arm maneuvers instruments close to the surface. These instruments and tools are housed in a "turret" that can switch to the appropriate tool at the time.
Developer(s): Maxar Technologies, MDA Space
Country: United States
First Use Date: 2012
Status: Operational
Reach (m): 2.2
Degrees of Freedom: 5
Grapple Type: 5 Scientific Instruments, Drill

7.1.17 RM17: Mars Surveyor 2001 Robotic Arm

Description: The Mars Surveyor 2001 Lander was scheduled to carry both a robotic arm and rover to support various science and technology experiments. This mission was cancelled, but the lander and robotic arm were eventually repurposed as the Phoenix lander in 2007.
Developer(s): NASA Jet Propulsion Laboratory (JPL)
Country: United States
First Use Date: 2001
Status: Concluded
Reach (m): 2

Degrees of Freedom: 4
Grapple Type: Scoop, Scraping Blades, Electrometer

7.1.18 RM18: Mars Volatiles and Climate Surveyor Robotic Arm (MVACS)

Description: The Mars Volatiles and Climate Surveyor (MVACS) suite of instruments was intended to land on Mars aboard the Mars Polar Lander in 1999. The primary purpose of the MVACS Robotic Arm was 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(s): National Aeronautics and Space Administration (NASA), University of Arizona
Country: United States
First Use Date: 1999
Status: Concluded
Reach (m): 2.2
Degrees of Freedom: 4
Grapple Type: Scoop, Temp probe, Camera

7.1.19 RM19: Mobile Metamaterial Internal Co-Integrator (MMIC-I) [ARMADAS]

Description: The Mobile Metamaterial Internal Co-Integrator (MMIC-I) serves as the ARMADAS integration robot. It is used for internal climbing and completing inter-voxel connections using bolts.
Developer(s): NASA Ames Research Center (ARC)
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

7.1.20 RM20: 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 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(s): National Aeronautics and Space Administration (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

7.1.21 RM21: 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(s): Defense Advanced Research Projects Agency (DARPA), MDA Space
Country: United States
First Use Date: 2007
Status: Completed
Reach (m): 2.8
Degrees of Freedom: 6
Grapple Type: Mouse Trap, Cone, Probe

7.1.22 RM22: Perseverance Sample Handling Assembly (SHA)

Description: The Perseverance rover uses a 2.1-meter arm to support sample handling and science collection. Th turret at the end of the arm contains multiple instruments and tools to extract and store core samples, drill into regolith and rocks, and to take images and analyze the Martian environment.
Developer(s): Maxar Technologies, MDA Space
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

7.1.23 RM23: Phoenix Mars Lander Robotic Arm

Description: The robotic arm on the Phoenix lander 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(s): Maxar Technologies, MDA Space
Country: United States
First Use Date: 2008
Status: Completed
Reach (m): 2
Degrees of Freedom: 4
Grapple Type: Scoop, Camera

7.1.24 RM24: 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(s): University of Maryland Space Systems Laboratory (UMD SSL)
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

7.1.25 RM25: 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 General Motors manufacturing plants on Earth.
Developer(s): National Aeronautics and Space Administration (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

7.1.26 RM26: S1

Description: The S1, developed by Japanese startup GITAI, is a semi-autonomous, semi-teleoperated robotic arm capable of operating internal or external to on-orbit or lunar facilities. The S1 is able to excel in general purpose tasks often difficult for industrial robots, such as switch actuation, tool use, and soft object manipulation. In October of 2021, the robotic arm autonomously completed a number of common crew IVA tasks within the NanoRacks Bishop pressurized volume of the ISS.
Developer(s): GITAI
Country: Japan
First Use Date: 2021-10-13 00:00:00
Status: Completed
Reach (m): 1
Degrees of Freedom: 8 + 1
Grapple Type: Two Finger Gripper, Camera

7.1.27 RM27: S10

Description: The S10, in development by Japanese startup GITAI, is an autonomous robotic arm intended for commercial space station applications. This robotic arm is capable of manipulating large objects, such as spacecraft or payloads, autonomously or through teleoperation. Also, autonomous traverse of the arm itself is available by using grapple end effectors at both ends of the arm. Demonstration of the S10 within a simulated microgravity environment in an underwater experimental facility was completed in 2023
Developer(s): GITAI
Country: Japan
First Use Date: TBD
Status: In Development
Reach (m): 10
Degrees of Freedom: 7
Grapple Type: Internal Proprietary Interface, Camera, Tool Change Capability

7.1.28 RM28: S2

Description: The S2, developed by Japanese startup GITAI, is a dual autonomous robotic arm system expected to complete demonstrations outside of the NanoRacks Bishop airlock of the ISS in 2023. The intended demonstration will focus on operations specific to ISAM, including, installation of ORUs, mating electrical connectors, manipulation of thermal blankets, and fastening screws using screwdriver tool.
Developer(s): GITAI
Country: Japan
First Use Date: Scheduled for 2023
Status: In Development
Reach (m): 1.5
Degrees of Freedom: 7 + 1
Grapple Type: Two Finger Gripper, Camera, Tool Change Capability

7.1.29 RM29: Scaling Omnidirectional Lattice Locomoting Explorer (SOLL-E) [ARMADAS]

Description: The Scaling Omnidirectional Lattice Locomoting Explorer (SOLL-E) serves as the ARMADAS cargo robot. It is used for material transport and placement through an inchworming process on the exterior of the structure.
Developer(s): NASA Ames Research Center (ARC)
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

7.1.30 RM30: 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 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 3-meter communications antenna.
Developer(s): Maxar Technologies
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

7.1.31 RM31: STAARK

Description: STAARK is a modular, customizable robotic system developed by Redwire. It has a standardized tool interface to accommodate multiple end-effectors, including Redwire's own grippers. A vision system supports object tracking and provides grasping knowledge for grappling operations. The software enables teleoperation, assisted operation, and supervised autonomous operations.
Developer(s): Redwire Corporation
Country: United States
First Use Date: TBD
Status: In Development
Reach (m): 1.92
Degrees of Freedom: 6
Grapple Type: Multiple

7.1.32 RM32: 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(s): Russia
Country: Russia
First Use Date: 1986
Status: Operational
Reach (m): 14
Degrees of Freedom: Unavailable
Grapple Type: Unavailable

7.1.33 RM33: TALISMAN

Description: The Tendon-Actuated Lightweight In-Space MANipulator (TALISMAN) is a long reach manipulator arm that can be used for satellite servicing, small payload delivery, and large space observatory assembly.
Developer(s): NASA Langley Research Center (LaRC)
Country: United States
First Use Date: TBD
Status: In Development
Reach (m): 20
Degrees of Freedom: 5
Grapple Type: Swappable End effector

7.1.34 RM34: xLink Robotic Arm [OSAM-2]

Description: The Motiv xLink robotic arm plans to 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(s): Motiv Space Systems
Country: United States
First Use Date: Scheduled for 2024
Status: In Development
Reach (m): 1-3
Degrees of Freedom: 4-7
Grapple Type: Unavailable

7.2 RPO, Capture, Docking, and Mating

7.2.1 RCDM01: ADRAS-J

Description: ADRAS-J is a mission to safely approach and characterize an existing piece of large debris. The ADRAS-J spacecraft was selected by JAXA for Phase I of its Commercial Removal of Debris Demonstration (CRD2) Project, and is scheduled to launch in 2023 from New Zealand on a Rocket Lab Electron.
Developer: Astroscale, Japan Aerospace Exploration Agency (JAXA)
Country: Japan
First Use Date: Planned 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: Non-Cooperative

7.2.2 RCDM02: AeroCube-10

Description: The AeroCube-10 demonstration mission was a pair of 1.5U CubeSats (one with 28 deployable atmospheric probes and a laser beacon, another with a camera and propulsion system). AC-10B entered “orbit” around AC-10A and used its 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

7.2.3 RCDM03: ANGELS

Description: Automated Navigation and Guidance Experiment for Local Space (ANGELS) evaluated space situational awareness techniques in the region around its Delta-4 launch vehicle upper stage. The mission began experiments approximately 50 km away from the upper stage and progressed to within several kilometers using ground-commanded authorization to proceed at points throughout the experiment.
Developer: Air Force Research Laboratory (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

7.2.4 RCDM04: 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: National University of Defense Technology (NUDT), People’s Liberation Army (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

7.2.5 RCDM05: APAS [ISS]

Description: The Androgynous Peripheral Attachment System (APAS) is an androgynous docking mechanism used on the ISS. The system was first used on the ISS between U.S. Pressurized Mating Adapter 1 and the Russian Functional Cargo Block (FGB), also known as Zarya.
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

7.2.6 RCDM06: Argon Autonomous Rendezvous and Docking (AR&D) Sensor

Description: Argon was a ground-based demonstration module that 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 Goddard Space Flight Center (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

7.2.7 RCDM07: 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 U.S. and USSR and was constructed in the U.S.
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

7.2.8 RCDM08: COSMIC

Description: The Cleaning Outer Space Mission through Innovative Capture (COSMIC) will harness Astroscale's RPO and robotic debris capture capabilities to remove two defunct British satellites currently orbiting Earth by 2026.
Developer: Astroscale, United Kingdom Space Agency (UKSA)
Country: Japan, UK
First Use Date: Planned for 2026
Status: In Development
Contact vs. Non-contact: Contact
Misalignment Tolerance: N/A
Max RPO Initiation Distance (m): Unavailable
Cooperative vs. Non-Cooperative: Non-Cooperative

7.2.9 RCDM09: ELSA-d

Description: The End-of-Life Services by Astroscale-demonstration (ELSA-d) mission consists of a servicer satellite and a client satellite launched together. The servicer satellite was developed to safely remove debris objects from orbit, equipped with proximity rendezvous technologies and a magnetic docking mechanism. The client satellite simulates a piece of debris fitted with a ferromagnetic plate to enable docking with the servicer satellite.
Developer: Astroscale
Country: Japan
First Use Date: 2021
Status: Completed
Contact vs. Non-contact: Contact
Misalignment Tolerance: N/A
Max RPO Initiation Distance (m): Unavailable
Cooperative vs. Non-Cooperative: Cooperative

7.2.10 RCDM10: ELSA-M

Description: The End-of-Life Service by Astroscale – Multiple (ELSA-M) servicer spacecraft leverages flight heritage technology, systems, and capability developed during the ELSA-d mission. The servicer will be able to provide end-of-life services to a range of future satellite operators, including constellations, which are equipped with a compatible magnetic capture mechanism such as the Astroscale Docking Plate. An ELSA-M in-orbit demonstration with a customer satellite is planned for 2025.
Developer: Astroscale
Country: Japan

First Use Date: Planned for 2025
Status: In Development
Contact vs. Non-contact: Contact
Misalignment Tolerance: N/A
Max RPO Initiation Distance (m): Unavailable
Cooperative vs. Non-Cooperative: Non-Cooperative

7.2.11 RCDM11: Engineering Test Satellite VII (ETS-VII)

Description: ETSVII (Japanese nickname: Kiku7) was a JAXA (formerly NASDA) technology demonstration satellite. The overall mission objectives were to conduct space robotic experiments and to demonstrate its utility for robotic orbital operation and servicing tasks (e.g., rendezvous and docking techniques).
Developer: Japan Aerospace Exploration Agency (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

7.2.12 RCDM12: HelioSwarm

Description: The HelioSwarm mission is a constellation of nine spacecraft that will capture multiple in-space measurements of solar wind and magnetic field fluxuations from different points in space. HelioSwarm will consist of one hub spacecraft and eight co-orbiting small satellites that range in distance from each other and the hub spacecraft.
Developer: National Aeronautics and Space Administration (NASA)
Country: USA
First Use Date: 2028
Status: In Development
Contact vs. Non-contact: Non-Contact
Misalignment Tolerance: N/A
Max RPO Initiation Distance (m): Unavailable
Cooperative vs. Non-Cooperative: Cooperative

7.2.13 RCDM13: International Berthing and Docking Mechanism (IBDM) [ISS]

Description: The International Berthing & Docking Mechanism (IBDM) is composed of a soft docking system (facilitates alignment and mechanical latches achieve soft capture) and a hard docking system (creates the sealed interface). The androgynous docking system is contact-force sensing, magnetically latched for capture, low impact, and capable of docking and berthing large and small vehicles.
Developer: European Space Agency (ESA), QinetiQ Space, Sierra Nevada Corporation, SENER, RUAG,

Maxon Group
Country: European Space Agency (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

7.2.14 RCDM14: LEO Knight

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

7.2.15 RCDM15: Mission Extension Vehicle (MEV)

Description: The Mission Extension Vehicle (MEV) is the first commercial 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

7.2.16 RCDM16: Mission Robotic Vehicle (MRV) [RSGS]

Description: A future on-orbit servicing bus developed using technologies and lessons from the Mission Extension Vehicle. The robotic payload will be supplied by DARPA and developed by the U.S. Naval

Research Laboratory as part of the Robotic Servicing of Geosynchronous Satellites (RSGS) mission.
Developer: Northrop 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

7.2.17 RCDM17: Mycroft

Description: Mycroft is a 4th-generation experimental Space Situational Awareness (SSA) spacecraft that builds upon technology, knowledge, and lessons learned from XSS-10, XSS-11, and ANGELS. The mission is exploring ways to enhance space object characterization by evaluating the region around EAGLE using an SSA camera, and it uses sensors and software to perform advanced guidance, navigation, and control functions.
Developer: Air Force Research Laboratory (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

7.2.18 RCDM18: 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. The Linear Actuator System (LAS), designed and built by MOOG, provides mutli-axis independent load control for soft capture docking without a robotic arm. The NDS Block 1 is intended for use with ISS and the Block 2 will be used on Gateway. The Block 2 variant will support fluid transfer through the MOOG fluid transfer coupling.
Developer: National Aeronautics and Space Administration (NASA), MOOG
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

7.2.19 RCDM19: Nautilus

Description: Developed by Starfish Space, the Nautilus capture mechanism attaches to satellites for docking and manipulation. It is a reusable concept that can adhere to multiple capture surfaces, even those not designed for docking, and can provide dynamic damping between the servicer and client spacecraft.
Developer: Starfish Space
Country: USA
First Use Date: TBD
Status: In Development
Contact vs. Non-contact: Contact
Misalignment Tolerance: N/A
Max RPO Initiation Distance (m): Unavailable
Cooperative vs. Non-Cooperative: Non-Cooperative

7.2.20 RCDM20: Orbital Express

Description: Launched March 8, 2007 as part of the United States Air Force Space Test 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: Defense Advanced Research Projects Agency (DARPA), National Aeronautics and Space Administration (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

7.2.21 RCDM21: OSAM-1

Description: OSAM-1 is a spacecraft under development by NASA and Maxar which will demonstrate activities required for unplanned satellite mission extension. OSAM-1 will rendezvous with and refuel Landsat 7, which will require activities such as cutting insulation, unscrewing bolts and caps, and attaching propellant lines. After completing refuel of Landsat 7, the hosted SPIDER payload will assemble a communications antenna.
Developer: National Aeronautics and Space Administration (NASA), Maxar Technologies
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

7.2.22 RCDM22: Otter

Description: Otter, from Starfish Space, is a low cost, rapidly deployable ~ 200 kg space tug to perform life extension missions in GEO and end-of-life satellite removal missions in LEO. Otter leverages Starfish Space's other developments, CEPHALOPOD guidance and control software which is currently on orbit, CETACEAN relative navigation software, and Nautilus capture mechanism.
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

7.2.23 RCDM23: Otter Pup

Description: Otter Pup is a demonstration mission to test RPOD and docking with another spacecraft on orbit. The mission uses Starfish Space's technologies to rendezvous and capture the Launcher Space's Orbiter spacecraft (which also delivered Otter Pup to orbit). An anomaly during deployment from Orbiter has put the completion of the demonstration's objectives in jeopardy.
Developer: Starfish Space
Country: United States
First Use Date: 2023
Status: Operational
Contact vs. Non-contact: Contact
Misalignment Tolerance: Unavailable
Max RPO Initiation Distance (m): Unavailable
Cooperative vs. Non-Cooperative: Non-Cooperative

7.2.24 RCDM24: PMA [ISS]

Description: A Pressurized Mating Adapter (PMA) converts 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: The Boeing Company
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

7.2.25 RCDM25: RAVEN [ISS]

Description: Raven is a technology demonstration module on the International Space Station that tests key elements of a new autonomous RPO system. Raven contains sensors, algorithms, and a high-speed processor to advance the capability to detect and track objects in space, which was demonstrated on ISS.
Developer: NASA Goddard Space Flight Center (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

7.2.26 RCDM26: SCOUT-Vision

Description: SCOUT-Vision is a space situational awareness payload that was launched in 2021 to provide data to support identification and tracking of objects in its vicinity.
Developer: SCOUT Space Inc
Country: United States
First Use Date: 2021
Status: Operational
Contact vs. Non-contact: Non-Contact
Misalignment Tolerance: N/A
Max RPO Initiation Distance (m): Unavailable
Cooperative vs. Non-Cooperative: Both

7.2.27 RCDM27: 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: National Aeronautics and Space Administration (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

7.2.28 RCDM28: 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: National Aeronautics and Space Administration (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

7.2.29 RCDM29: 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 reaction wheel assemblies with new models; Installed a new fine guidance sensor, voltage/temperature improvement kit, spare solid-state recorder, and S-Band single access transmitter; and replaced HST's computer, new outer blanket layers, and shell/shield replacement fabric. New thermal insulation blankets were also installed.
Developer: National Aeronautics and Space Administration (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

7.2.30 RCDM30: Servicing Mission 3B (STS-109) [HST]

Description: STS-109 was the fourth servicing mission of the HST. During this mission, a new instrument, the Faint Object Camera, replaced the Fine Guidance Sensor, the last original instrument on the HST. In addition, a cooler was installed to revive the Near Infrared Camera and Multi-Object Spectrometer and the solar arrays were replaced. The Shuttle also boosted HST during this mission.

Developer: National Aeronautics and Space Administration (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

7.2.31 RCDM31: Servicing Mission 4 (STS-125) [HST]

Description: STS-125 was the fifth and final servicing mission to HST. The mission included the installation of Wide Field Camera 3 and Cosmic Origins Spectrograph instruments, repair of the Space Telescope Imaging Spectrograph and Advanced Camera for Surveys , replacement of rate unit sensors and batteries, and installation of a soft capture mechanism and new outer blanket layers for thermal protection.

Developer: National Aeronautics and Space Administration (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

7.2.32 RCDM32: Shijian-17

Description: Shijian-17 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

7.2.33 RCDM33: 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

7.2.34 RCDM34: SSVP

Description: Sistema Stykivki I Vnutrennego Perekhoda (SSVP) is the docking standard used by Soviet and Russian spacecraft such as the Soyuz, Progress, and Mir. It is sometimes called the Russian Docking System.
Developer: TsKBEM
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

7.2.35 RCDM35: Tanker-001 Tenzing

Description: Operational fuel depot storing green propellant High-Test Peroxide. Contains the Rapidly Attachable Fluid Transfer Interface (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: Orbit Fab
Country: United States
First Use Date: 2021-06-30**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

7.2.36 RCDM36: XSS-10

Description: The eXperimental Small Satellite – 10 (XSS-10) technology demonstration micro-satellite launched in 2003 and demonstrated line of sight guidance and proximity operations with another space object (the Delta 2 second stage it was launched on).
Developer: Air Force Research Laboratory (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

7.2.37 RCDM37: XSS-11

Description: The eXperimental Small Satellite – 11 (XSS-11) technology demonstration micro-satellite was a follow-on to the successful XSS-10 demonstration. XSS-11 demonstrated technologies necessary to plan and evaluate autonomous rendezvous and proximity operations with an expended rocket body and other space objects near its orbit.
Developer: Air Force Research Laboratory (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

7.3 RELOCATION

7.3.1 R01: Aolong-1

Description: Aolong-1 is a Chinese developed satellite that 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: National University of Defense Technology (NUDT), People’s Liberation Army (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

7.3.2 R02: ELSA-d

Description: The End-of-Life Services by Astroscale-demonstration (ELSA-d) mission consists of a servicer satellite and a client satellite launched together. The servicer satellite was developed to safely remove debris objects from orbit, equipped with proximity rendezvous technologies and a magnetic docking mechanism. The client satellite simulates a piece of debris fitted with a ferromagnetic plate to enable docking with the servicer satellite.
Developer: Astroscale
Country: Japan
First Use Date: 2021
Status: Completed
Intended Transit: debris removal
Max. Client Mass: 20 kg
Thruster / Propellant Type: green chemical

7.3.3 R03: ION Satellite Carrier

Description: The ION Satellite Carrier is a satellite dispenser platform that can deliver a range of different sized payloads to LEO. The configurable payload bay could carry a combination of launch dispensers, CubeSate-sized payloads, microsatellites, and other instruments. The platform is able to perform orbital maneuvers between payload deployments. As of June 2023, eleven missions have launched.
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

7.3.4 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: National Aeronautics and Space Administration (NASA), Roscosmos
Country: United States, Russia
First Use Date: Unavailable
Status: Operational
Intended Transit: LEO
Max. Client Mass: N/A

Thruster / Propellant Type: Chemical

7.3.5 R05: Mission Extension Pods (MEP)

Description: Mission Extension Pods are Northrop Grumman's next generation of servicing vehicles. They will provide smaller and less expensive life extension services that perform orbit control, providing up to six years of life extension. They will be installed by a Mission Robotic Vehicle which can carry several pods to multiple client spacecraft.
Developer: Northrop 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

7.3.6 R06: Mission Extension Vehicle (MEV)

Description: The Mission Extension Vehicle (MEV) is the first commercial 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
Intended Transit: GEO
Max. Client Mass: Unavailable
Thruster / Propellant Type: Electric

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

Description: A future on-orbit servicing bus developed using technologies and lessons from the Mission Extension Vehicle. The robotic payload will be supplied by DARPA and developed by the U.S. Naval Research Laboratory as part of the Robotic Servicing of Geosynchronous Satellites (RSGS) mission.
Developer: Northrop Grumman
Country: United States
First Use Date: TBD
Status: In Development
Intended Transit: GEO
Max. Client Mass: Unavailable

Thruster / Propellant Type: Electric

7.3.8 R08: Orbital Maneuvering Vehicle (OMV)

Description: The Orbital Maneuvering Vehicle (OMV) is an ESPA-based space tug used for orbital relocation of secondary payloads. OMV offers a variety of sizes and configurations, and it 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

7.3.9 R09: Orbiter

Description: Orbiter is a space tug and payload delivery system developed by Launcher Space for use in LEO. Orbiter is designed to operate as part of a rideshare or a dedicated launch. The first launch of this system occurred in 2023 to deliver satellites to orbit, and an anomaly forced an early deployment of its payloads.
Developer: Launcher Space
Country: United States
First Use Date: 2023
Status: Operational
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

7.3.10 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

7.3.11 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: National Aeronautics and Space Administration (NASA)
Country: United States
First Use Date: 1993
Status: Completed
Intended Transit: Orbit raising
Max. Client Mass: N/A
Thruster / Propellant Type: Chemical

7.3.12 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: National Aeronautics and Space Administration (NASA)
Country: United States
First Use Date: 1997
Status: Completed
Intended Transit: Orbit raising
Max. Client Mass: N/A
Thruster / Propellant Type: Chemical

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

Description: STS-109 was the fourth servicing mission of the HST. During this mission, a new instrument, the Faint Object Camera, replaced the Fine Guidance Sensor, the last original instrument on the HST. In addition, a cooler was installed to revive the Near Infrared Camera and Multi-Object Spectrometer and the solar arrays were replaced. The Shuttle also boosted HST during this mission.
Developer: National Aeronautics and Space Administration (NASA)
Country: United States
First Use Date: 2002
Status: Completed

Intended Transit: Orbit raising
Max. Client Mass: N/A
Thruster / Propellant Type: Chemical

7.3.14 R14: Sherpa

Description: Spaceflight's Sherpa family of orbital transfer vehicles are based on an ESPA-class deployment system. The base unit, Sherpa-FX, was first flown in 2021 and hosts multiple payloads, provides telemetry, and deploys at different timings during the mission. The Sherpa-AC additionally provides a flight computer, attitude knowledge, control, and is optimized for hosted payloads. The Sherpa-LTC features a high thrust propulsion system that provides the ability to rapidly transfer orbits. The Sherpa-LTE provides high delta-V capability with its electric propulsion system 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 2023 and provides high delta-V bipropellant propulsion system for satellite delivery throughout cislunar space.
Developer: Spaceflight
Country: United States
First Use Date: 2021
Status: Operational
Intended Transit: Orbit raising and lowering, in-plane phasing, LTAN change
Max. Client Mass: Unavailable
Thruster / Propellant Type: Bi-propellant, green propulsion, Chemical Propulsion, electric propulsion, Xenon propellant

7.3.15 R15: Space Utility Vehicle (SUV)

Description: The Space Utility Vehicle (SUV) is a ESPA-based electric space tug system designed to launch with Firefly Aerospace's Alpha launch vehicle and potentially others. It is designed to insert payloads into LEO, GEO, and possibly cislunar space. While payloads are attached, the SUV can perform station keeping and provide services such as power and communication.
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

7.3.16 R16: Vigoride

Description: Vigoride is a space tug from Momentus, Inc., that is compatible with the ESPA Grande and designed for orbital plane changes, inclination adjustments, and payload delivery while also providing power, communications, and station keeping while attached to the tug. Momentus launched its third

Vigoride mission, Vigoride-6, in April 2023 aboard the SpaceX Transporter-7 mission. Vigoride-6 successfully deployed all of its customer payloads.
Developer: Momentus Inc
Country: United States
First Use Date: 2022
Status: Operational
Intended Transit: Orbit raising and deraising mainly in low earth orbits
Max. Client Mass: 750 kg
Thruster / Propellant Type: water plasma engines

7.4 Planned Repair, Upgrade, Maintenance, and Installation

7.4.1 PRUMI01: Axon/Dactylus

Description: Tethers Unlimited's AXON connector is a low-profile soft capture end effector that can be used to connect two spacecraft together in orbit. The AXON connector is designed to be used with the KRAKEN robotic arm to enable small robotic systems to perform complex servicing tasks on large space systems. The DACTYLUS servicing tool is a robotic tool that can be used for in-space servicing of satellites. The DACTYLUS tool is designed to be used with the KRAKEN robotic arm and the AXON connector to enable small robotic systems to perform complex servicing tasks on large space systems.
Developer: Tethers Unlimited Inc
Country: United States
First Use Date: TBD
Status: In Development
Operation Type: Modular Interface
ORU SwaP: Unavailable
Standard Interface Type: Unavailable

7.4.2 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 Inc
Country: United States
First Use Date: 2021-01-01 00:00:00
Status: Operational
Operation Type: Grapple interface
ORU SwaP: Unavailable
Standard Interface Type: Mechanical

7.4.3 PRUMI03: FuseBlox

Description: FuseBlox is an androgynous interface for mechanical, electrical, and data. Received Phase II SBIR funding from AFRL.
Developer: SpaceWorks Enterprises Inc
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

7.4.4 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 International Inc
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

7.4.5 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 Space Application Services 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

7.4.6 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 on-orbit servicing 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: German Space Agency (GSA)
Country: Germany
First Use Date: 2022
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

7.4.7 PRUMI07: ISS EVR Experiment

Description: The GITAI ISS EVR Experiment will be testing ISAM operations by two GITAI S2 robotic arm installed externally to the ISS NanoRacks Bishop Airlock. The experiment will include autonomous ISAM operations by the S2 robotic arms, including ORU manipulation, tool changing, fastener tightening and removal, thermal blanket manipulation, connector mating and demating, and dual robotic arm cooperation. The experiment is expected to reach a TRL level of 7 through this demonstration.
Developer: GITAI
Country: Japan
First Use Date: 2023
Status: In Development
Operation Type: Robotic Servicing
ORU SwaP: N/A
Standard Interface Type: General Gripper

7.4.8 PRUMI08: ISS IVR Experiment

Description: During the GITAI IVR ISS Experiment, a S1 robotic arm completed a number of operations within the Nanoracks Bishop Airlock pressurized volume of the ISS. This experiment involved the robotic arm assembling a four-panel solar array mockup and completing a number of IVA tasks on a taskboard with standard IVA operations. The robot completed these operations autonomously and through teleoperations from a ground station in Houston.

Developer: GITAI
Country: Japan
First Use Date: 2021-10-16 00:00:00
Status: Completed
Operation Type: Robotic Servicing
ORU SwaP: N/A
Standard Interface Type: General Gripper

7.4.9 PRUMI09: Mag Tag

Description: EPM-based latching connector for enabling repair, fluid transfer, modular upgrades, and payload swapping.
Developer: Altius Space Machines Inc
Country: United States
First Use Date: TBD
Status: In Development
Operation Type: Modular Interface
ORU SwaP: Unavailable
Standard Interface Type: Mechanical

7.4.10 PRUMI10: Orbital Express

Description: Launched March 8, 2007 as part of the United States Air Force Space Test 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: Defense Advanced Research Projects Agency (DARPA), National Aeronautics and Space Administration (NASA)
Country: United States
First Use Date: 2007
Status: Completed
Operation Type: Servicer
ORU SwaP: Unavailable
Standard Interface Type: Data, Power, Mechanical

7.4.11 PRUMI11: Rendezvous, Proximity Operations, and Docking (RPOD) Kit

Description: The Rendezvous, Proximity Operations, and Docking (RPOD) Kit is a turnkey solution for spacecraft to autonomously dock in space, offering services like asset inspection, refueling, and satellite life-extension. It is designed for cooperative docking missions, featuring low mass, power consumption,

and compatibility with various docking interfaces and propulsion systems, with fleet performance improvement through software updates after each mission. For uncooperative missions or robotic arm usage, specific mission needs can be discussed with the company.
Developer: Obruta 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

7.4.12 PRUMI12: Roll-Out Solar Array (ROSA)

Description: The Roll-Out Solar Array (ROSA) is a NASA-developed, flexible, rollable solar panel technology for space applications, offering a more compact design compared to traditional rigid panels. The ROSA investigation evaluates deployment, retraction, shape changes during solar obstruction, and other physical challenges to assess the array's strength and durability. It was first tested on the International Space Station in 2017.
Developer: National Aeronautics and Space Administration (NASA)
Country: United States
First Use Date: 3 Launches beginning in 2021
Status: Operational
Operation Type: Modular Interface
ORU SwaP: Unavailable
Standard Interface Type: Mechanical, Power, Data

7.4.13 PRUMI13: 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: National Aeronautics and Space Administration (NASA)
Country: United States
First Use Date: 1993
Status: Completed
Operation Type: Servicer
ORU SwaP: Unavailable
Standard Interface Type: N/A

7.4.14 PRUMI14: 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: National Aeronautics and Space Administration (NASA)
Country: United States
First Use Date: 1997
Status: Completed
Operation Type: Servicer
ORU SwaP: Unavailable
Standard Interface Type: N/A

7.4.15 PRUMI15: 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 reaction wheel assemblies with new models; Installed a new fine guidance sensor, voltage/temperature improvement kit, spare solid-state recorder, and S-Band single access transmitter; and replaced HST's computer, new outer blanket layers, and shell/shield replacement fabric. New thermal insulation blankets were also installed.
Developer: National Aeronautics and Space Administration (NASA)
Country: United States
First Use Date: 1999
Status: Completed
Operation Type: Servicer
ORU SwaP: Unavailable
Standard Interface Type: N/A

7.4.16 PRUMI16: Servicing Mission 3B (STS-109) [HST]

Description: STS-109 was the fourth servicing mission of the HST. During this mission, a new instrument, the Faint Object Camera, replaced the Fine Guidance Sensor, the last original instrument on the HST. In addition, a cooler was installed to revive the Near Infrared Camera and Multi-Object Spectrometer and the solar arrays were replaced. The Shuttle also boosted HST during this mission.
Developer: National Aeronautics and Space Administration (NASA)
Country: United States
First Use Date: 2002
Status: Completed
Operation Type: Servicer
ORU SwaP: Unavailable

Standard Interface Type: N/A

7.4.17 PRUMI17: Servicing Mission 4 (STS-125) [HST]

Description: STS-125 was the fifth and final servicing mission to HST. The mission included the installation of Wide Field Camera 3 and Cosmic Origins Spectrograph instruments, repair of the Space Telescope Imaging Spectrograph and Advanced Camera for Surveys , replacement of rate unit sensors and batteries, and installation of a soft capture mechanism and new outer blanket layers for thermal protection.
Country: United States
First Use Date: 2009
Status: Completed
Operation Type: Servicer
ORU SwaP: Unavailable
Standard Interface Type: N/A

7.4.18 PRUMI18: 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. Athena is a joint program between NASA, NOAA, NovaWurks, and the Air Force Space and Missile Systems Center that will measure solar energy that Earth reflects and absorbs, gathered via a very small telescope attached to a NovaWurks Payload Accommodation Configuration (PAC). Athena is described as "... a test of NovaWurks' quick-turnaround capability."
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

7.4.19 PRUMI19: 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. Mass of <10kg Peak Power <100W.
Standard Interface Type: N/A

7.4.20 PRUMI20: Standard Interface for Robotic Manipulation of Payloads in Future Space Missions (SIROM)

Description: SIROM offers three configurations of a standardized interface (Active-Passive, Active, and Passive) with distinct features for mating, alignment, and data/power transmission. It enables direct interaction with cooperative structures for servicing and standardizes interfaces for mechanical, data, electrical, and fluid connections. Notably, SIROM finds applications in satellite payload upgrades or replacements.
Developer: European Space Agency (ESA)
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: Unavailable
Power: 3000 W
Data: 200 – 1000 Mbps
Fluid Rate: 0.3L/min @ 1 bar
Thermal: 2-2.5 kW
Standard Interface Type: Mechanical, Fluid(Thermal), Power, Data

7.5 Unplanned or Legacy Repair and Maintenance

7.5.1 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 Inc
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

7.5.2 ULRM02: Mission Extension Pods (MEP)

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: Northrop 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

7.5.3 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: Northrop 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

7.5.4 ULRM04: OSAM-1

Description: OSAM-1 is a spacecraft under development by NASA and Maxar which will demonstrate activities required for unplanned satellite mission extension. OSAM-1 will rendezvous with and refuel Landsat 7, which will require activities such as cutting insulation, unscrewing bolts and caps, and attaching propellant lines. After completing refuel of Landsat 7, the hosted SPIDER payload will assemble a communications antenna.
Developer: National Aeronautics and Space Administration (NASA), Maxar Technologies
Country: United States
First Use Date: Scheduled for 2025
Status: In Development
Repairable Subsystems / Components: Refueling, others unavailable
Repair Tools: Dexterous Robotic Arms (2), Space Infrastructure Dexterous Robot (SPIDER), Autonomous Real-time Relative Navigation System, Servicing Avionics, Advanced Tool Drive and Tools, Propellant

Transfer System
Grapple Types: 2 robotic arms, SPIDER arm

7.5.5 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: National Aeronautics and Space Administration (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

7.5.6 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: National Aeronautics and Space Administration (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

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

Description: STS-125 was the fifth and final servicing mission to HST. The mission included the installation of Wide Field Camera 3 and Cosmic Origins Spectrograph instruments, repair of the Space Telescope Imaging Spectrograph and Advanced Camera for Surveys , replacement of rate unit sensors and batteries, and installation of a soft capture mechanism and new outer blanket layers for thermal protection.
Developer: National Aeronautics and Space Administration (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

7.5.8 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: National Aeronautics and Space Administration (NASA)
Country: United States
First Use Date: 2013
Status: Completed
Repairable Subsystems / Components: N/A
Repair Tools: N/A
Grapple Types: Small sniper, slicer, and manipulator

7.6 Refueling and Fluid Transfer

7.6.1 RFT01: Cooperative Service Valve (CSV)

Description: The CSV is a spacecraft Fill and Drain Valve for cooperative servicing, featuring a robotic interface, three individually actuated seals, a self-contained anti-back drive system, and built-in thermal isolation. It transfers loads to the mounting structure, prevents accidental actuation, and has four fluid configurations with unchanged geometry. Unique keying and color-coding prevent media mixing and operator error.
Developer: National Aeronautics and Space Administration (NASA)
Country: United States
First Use Date: Unknown

Status: In Development
Propellant / Fluid Type: Pressurant / Hydrazine / MMH / NTO
Fuel Volume / Mass: Unavailable
Boil – Off Rate: Unavailable

7.6.2 RFT02: 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: National Aeronautics and Space Administration (NASA)
Country: United States
First Use Date: 2018
Status: Completed
Propellant / Fluid Type: Methane
Fuel Volume / Mass: 42 liters
Boil – Off Rate: ~Zero

7.6.3 RFT03: 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 Marshall Space Flight Center (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

7.6.4 RFT04: Fluid Acquisition & Resupply Experiment II (FARE-II)

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

7.6.5 RFT05: 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

7.6.6 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: National Aeronautics and Space Administration (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

7.6.7 RFT07: 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: National Aeronautics and Space Administration (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

7.6.8 RFT08: 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. The Linear Actuator System (LAS), designed and built by MOOG, provides multi-axis independent load control for soft capture docking without a robotic

arm. The NDS Block 1 is intended for use with ISS and the Block 2 will be used on Gateway. The Block 2 variant will support fluid transfer through the MOOG fluid transfer coupling.
Developer: National Aeronautics and Space Administration (NASA), MOOG
Country: United States
First Use Date: 2018
Status: Operational
Propellant / Fluid Type: Xenon and bi-propellant
Fuel Volume / Mass: Unavailable
Boil – Off Rate: Unavailable

7.6.9 RFT09: 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: National Aeronautics and Space Administration (NASA), Eta Space, Lockheed Martin, SpaceX, United Launch Alliance (ULA)
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

7.6.10 RFT10: 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: National Aeronautics and Space Administration (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

7.6.11 RFT11: Orbital Express

Description: Launched March 8, 2007 as part of the United States Air Force Space Test 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: Defense Advanced Research Projects Agency (DARPA), National Aeronautics and Space Administration (NASA)
Country: United States
First Use Date: 2007
Status: Completed
Propellant / Fluid Type: Hydrazine
Fuel Volume / Mass: Unknown
Boil – Off Rate: N/A

7.6.12 RFT12: 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 Johnson Space Center (JSC)
Country: United States
First Use Date: 1984
Status: Completed
Propellant / Fluid Type: Hydrazine
Fuel Volume / Mass: 142 kg
Boil – Off Rate: N/A

7.6.13 RFT13: OSAM-1

Description: OSAM-1 is a spacecraft under development by NASA and Maxar which will demonstrate activities required for unplanned satellite mission extension. OSAM-1 will rendezvous with and refuel

Landsat 7, which will require activities such as cutting insulation, unscrewing bolts and caps, and attaching propellant lines. After completing refuel of Landsat 7, the hosted SPIDER payload will assemble a communications antenna.
Developer: National Aeronautics and Space Administration (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

7.6.14 RFT14: 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, European Space Agency (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

7.6.15 RFT15: 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: National Aeronautics and Space Administration (NASA)
Country: United States
First Use Date: 2011
Status: Completed
Propellant / Fluid Type: Ethanol
Fuel Volume / Mass: 1.7 liters

Boil – Off Rate: Unavailable

7.6.16 RFT16: 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 Goddard Space Flight Center (GSFC)
Country: United States
First Use Date: 2018
Status: Completed
Propellant / Fluid Type: Methane
Fuel Volume / Mass: 42 liters
Boil – Off Rate: ~Zero

7.6.17 RFT17: 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: National Aeronautics and Space Administration (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

7.6.18 RFT18: 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

7.6.19 RFT19: 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 Corporation
Country: United States
First Use Date: 1985
Status: Completed
Propellant / Fluid Type: Water
Fuel Volume / Mass: 16.8 liters
Boil – Off Rate: N/A

7.6.20 RFT20: 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: National Aeronautics and Space Administration (NASA)
Country: United States
First Use Date: 1993
Status: Completed
Propellant / Fluid Type: Helium
Fuel Volume / Mass: 152 liters
Boil – Off Rate: > 0

7.6.21 RFT21: 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: Orbit Fab
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

7.6.22 RFT22: 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 (NUDT)
Country: China
First Use Date: 2016
Status: Completed
Propellant / Fluid Type: Unavailable
Fuel Volume / Mass: Unavailable
Boil – Off Rate: Unavailable

7.7 Structural Manufacturing and Assembly

7.7.1 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: National Aeronautics and Space Administration (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
Material Types: Carbon-fiber-reinforced polymer, adaptable to metals
Joining: Androgynous Joints
Assembly Agent: Robot
Operation Regime: On-Orbit, In-Space, Terrestrial
Technology Area: Structure Joint

7.7.2 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: National Aeronautics and Space Administration (NASA)
Country: United States
First Use Date: TBD
Status: In Development
Max Dimensions: System is material supply governed, demonstrated at 5.8m
Material Types: Demonstrated with Carbon-fiber-reinforced polymer, adaptable to metals, ceramics
Joining: Robotically actuated mechanical fasteners
Assembly Agent: Robot
Operation Regime: On-Orbit, In-Space, Terrestrial
Technology Area: Robotic Assembly

7.7.3 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 Langley Research Center (LaRC)
Country: United States
First Use Date: TBD
Status: In Development
Max Dimensions: "Scalable"
Material Types: Metal Structure
Joining: N/A (end-effector)
Assembly Agent: Robot
Operation Regime: On-Orbit, In-Space, Terrestrial
Technology Area: Robotic Assembly

7.7.4 SMA04: CAS [ISS]

Description: Common Attachment System – First used between ESP3 logistics carrier and the P3 zenith CAS suite on the ISS.
Developer: National Aeronautics and Space Administration (NASA)
Country: United States
First Use Date: 2009
Status: Operational
Max Dimensions: Contact
Material Types: Metal Structure
Joining: Module Joint
Assembly Agent: Robot / EVA
Operation Regime: On-Orbit

Technology Area: Structure Joint

7.7.5 SMA05: EASE/ACCESS

Description: Space shuttle flight experiments that studied astronaut efficiency, fatigue, and construction and maintenance techniques for construction of space structures.
Developer: National Aeronautics and Space Administration (NASA)
Country: United States
First Use Date: 1985
Status: Completed
Max Dimensions: 3.7m tetrahedral truss
Material Types: Metal Structure
Joining: Nodal Joints
Assembly Agent: Human
Operation Regime: On-Orbit, ISS
Technology Area: Human Assembly

7.7.6 SMA06: ESAMM

Description: Extended Structure Additive Manufacturing Machine (ESAMM) is the subsystem that plans to additively manufacture the extended structures for OSAM-2.
Developer: Redwire Corporation
Country: United States
First Use Date: Planned for 2023
Status: In Development
Max Dimensions: 0.84m
Material Types: Metal Structure
Joining: 3D printed
Assembly Agent: Robot
Operation Regime: On Orbit
Technology Area: Robotic Arm/Assembly

7.7.7 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: National Aeronautics and Space Administration (NASA)
Country: United States
First Use Date: N/A
Status: N/A

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

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

Description: Structural Components Assembled to give ISS Frame/Support.
Developer: National Aeronautics and Space Administration (NASA)
Country: United States
First Use Date: 1998
Status: Operational
Max Dimensions: 110m
Material Types: Metal Structure
Joining: Bolted Joints
Assembly Agent: Robot / EVA
Operation Regime: On-Orbit
Technology Area: Robotic Arm/Assembly, Human Assembly, Deployable

7.7.9 SMA09: ISS EVR Experiment

Description: The GITAI ISS EVR Experiment will be testing ISAM operations by two GITAI S2 robotic arm installed externally to the ISS NanoRacks Bishop Airlock. The experiment will include autonomous ISAM operations by the S2 robotic arms, including ORU manipulation, tool changing, fastener tightening and removal, thermal blanket manipulation, connector mating and demating, and dual robotic arm cooperation. The experiment is expected to reach a TRL level of 7 through this demonstration.
Developer: GITAI
Country: Japan
First Use Date: 2023
Status: In Development
Max Dimensions: N/A
Material Types: N/A
Joining: Robotically Assembled Joints
Assembly Agent: Robot
Operation Regime: On-Orbit, In-Space, Terrestrial
Technology Area: Robotic Assembly

7.7.10 SMA10: ISS IVR Experiment

Description: During the GITAI ISS IVR Experiment, a S1 robotic arm completed a number of operations within the Nanoracks Bishop Airlock pressurized volume of the ISS. This experiment involved the robotic

arm assembling a four-panel solar array mockup and completing a number of IVA tasks on a taskboard with standard IVA operations. The robot completed these operations autonomously and through teleoperations from a ground station in Houston.
Developer: GITAI
Country: Japan
First Use Date: 2021-10-16
Status: Completed
Max Dimensions: N/A
Material Types: N/A
Joining: Robotically Assembled Joints
Assembly Agent: Robot
Operation Regime: On-Orbit, In-Space, Terrestrial
Technology Area: Robotic Assembly

7.7.11 SMA11: 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: National Aeronautics and Space Administration (NASA)
Country: United States
First Use Date: N/A
Status: N/A
Max Dimensions: N/A
Material Types: N/A
Joining: E-Beam Welding
Assembly Agent: Robot/Human
Operation Regime: On-Orbit, In-Space
Technology Area: Structure Joint

7.7.12 SMA12: MakerSat

Description: As a part of the OSAM-1 mission, the Beam Fabricator planned to demonstrate the manufacturing of a 3D printed beam in space.
Developer: Tethers Unlimited Inc
Country: United States
First Use Date: Planned for 2025
Status: Concluded
Max Dimensions: 10m Truss Fabricated
Material Types: Carbon Fiber
Joining: "Extrusion with Post Assembly"
Assembly Agent: Robot

Operation Regime: On-Orbit, In-Space
Technology Area: Robotic Assembly, manufacturing

7.7.13 SMA13: MRTAS [ISS]

Description: The ISS Modified Rocketdyne Truss Attachment Mechanism (MRTAS) is a crucial docking system on the International Space Station, ensuring a secure and flexible connection between truss segments and other components, facilitating assembly and maintenance during spacewalks. It employs alignment cones and spring-loaded "stingers" for initial connection and fine-tuning with bolts for the final attachment.
Developer: The Boeing Company
Country: United States
First Use Date: 2006
Status: Operational
Max Dimensions: Contact
Material Types: N/A
Joining: Custom Actuator Mechanism
Assembly Agent: Robot
Operation Regime: On-Orbit, In-Space
Technology Area: Structure Joint

7.7.14 SMA14: 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: National Aeronautics and Space Administration (NASA)
Country: United States
First Use Date: TBD
Status: In Development
Max Dimensions: 30 x 30 x 30 cube
Material Types: Metal Structure
Joining: N/A
Assembly Agent: Robot
Operation Regime: On-Orbit, In-Space, Terrestrial
Technology Area: Robotic Assembly

7.7.15 SMA15: OSAM-2

Description: The technology demonstration, previously called Archinaut One and now OSAM-2, plans to 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 (ESAMM).
Developer: Redwire Corporation, NASA Marshall Space Flight Center (MSFC)
Country: United States
First Use Date: Planned for 2024
Status: In Development
Max Dimensions: 10m for ESPA class satellites
Material Types: PEI/PC
Joining: 3D printed
Assembly Agent: Robot
Operation Regime: On-Orbit, In-Space
Technology Area: Robotic Assembly, manufacturing

7.7.16 SMA16: 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: National Aeronautics and Space Administration (NASA)
Country: United States
First Use Date: TBD
Status: In Development
Max Dimensions: "Scalable"
Material Types: Metal Structure
Joining: Nodal Joints
Assembly Agent: Robot
Operation Regime: On-Orbit, In-Space
Technology Area: Robotic Assembly

7.7.17 SMA17: 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: National Aeronautics and Space Administration (NASA)
Country: United States
First Use Date: Planned for 2025
Status: In Development
Max Dimensions: N/A
Material Types: Metal Structure
Joining: N/A
Assembly Agent: N/A
Operation Regime: On-Orbit, In-Space, Terrestrial
Technology Area: Robotic Arm Joint

7.7.18 SMA18: RTAS [ISS]

Description: Rocketdyne Truss Attachment System – First demonstrated when connecting ITS-P6 to Z1 on STS-97.
Developer: The Boeing Company
Country: United States
First Use Date: 2000
Status: Operational
Max Dimensions: Contact
Material Types: Metal Structure
Joining: Module Joint
Assembly Agent: Robot / EVA
Operation Regime: On-Orbit
Technology Area: Structure Joint

7.7.19 SMA19: 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: Union of Soviet Socialist Republics (USSR)
Country: USSR
First Use Date: 1984
Status: Completed
Max Dimensions: N/A
Material Types: Metal
Joining: Welding
Assembly Agent: Human
Operation Regime: On-Orbit
Technology Area: Welding

7.7.20 SMA20: 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: National Aeronautics and Space Administration (NASA)
Country: United States
First Use Date: TBD
Status: In Development
Max Dimensions: “Scalable”
Material Types: Composite
Joining: N/A

Assembly Agent: N/A
Operation Regime: On-Orbit, In-Space
Technology Area: Deployable

7.7.21 SMA21: 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: National Aeronautics and Space Administration (NASA), Westinghouse Electric Company
Country: United States
First Use Date: 1973
Status: Completed
Max Dimensions: 40 cm welding chamber
Material Types: Metal
Joining: Welding
Assembly Agent: Human
Operation Regime: On-Orbit
Technology Area: Welding

7.7.22 SMA22: 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: 2017-10-01 00:00:00
Status: Operational
Max Dimensions: “Scalable”
Material Types: Metal
Joining: Custom Actuator Mechanism
Assembly Agent: Robot
Operation Regime: On-Orbit, In-Space
Technology Area: Robotic Assembly

7.7.23 SMA23: 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 Technologies
Country: United States
First Use Date: Planned for 2025
Status: In Development
Max Dimensions: 5 m
Material Types: Metal Structure
Joining: N/A (end-effector)
Assembly Agent: Robot
Operation Regime: On-Orbit
Technology Area: Robotic Arm

7.7.24 SMA24: SSAS [ISS]

Description: The Segment-to-Segment Attachment System (SSAS) is an unpressurized device designed to securely link inboard truss components (such as truss P1 to S0). This fully automated mechanical system effectively aligns, captures, and subsequently fastens two truss elements together.
Developer: The Boeing Company
Country: United States
First Use Date: October, 2002
Status: Operational
Max Dimensions: Contact
Material Types: Metal Structure
Joining: Module Joint
Assembly Agent: Robot / EVA
Operation Regime: On-Orbit
Technology Area: Structure Joint

7.7.25 SMA25: 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: National Aeronautics and Space Administration (NASA)
Country: United States
First Use Date: N/A
Status: Concluded

Max Dimensions: N/A
Material Types: Composite
Joining: Bonded
Assembly Agent: N/A
Operation Regime: N/A
Technology Area: Structure Joint

7.7.26 SMA26: Strut Attachment, Manipulation, and Utility Robotic Aide (SAMURAI)

Description: A scalable modular strut/component attachment handling system; may be configured into various forms to handle a variety of system components, such as structure elements, structure module, or other modules that need to be assembled. Its function includes but not limited to component retrieve and attachment.
Developer: National Aeronautics and Space Administration (NASA)
Country: United States
First Use Date: TBD
Status: In Development
Max Dimensions: 46 in.
Material Types: Metal Structure
Joining: N/A
Assembly Agent: Robot
Operation Regime: On-Orbit, In-Space, Terrestrial
Technology Area: Robotic Assembly

7.7.27 SMA27: TCAM Soft Robotic Actuator

Description: The TCAM Soft Robotic Actuator is a concept for an in-space end effector which uses Twisted and Coiled Artificial Muscles (TCAMs). This concept is intended to be used in the construction of bonded segments of a large in-space assembled structure. The end effector design allows for conforming to conical struts and meets all manipulability, pressure, and temperature requirements of the intended use case.
Developer: NASA Langley Research Center (LaRC)
Country: United States
First Use Date: TBD
Status: In Development
Max Dimensions: N/A
Material Types: Soft Materials
Joining: N/A
Assembly Agent: Robot
Operation Regime: On-Orbit, In-Space, Terrestrial
Technology Area: Robotic Assembly

7.7.28 SMA28: 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: Union of Soviet Socialist Republics (USSR)
Country: USSR
First Use Date: 1969
Status: Completed
Max Dimensions: N/A
Material Types: Metal
Joining: Welding
Assembly Agent: Human
Operation Regime: On-Orbit
Technology Area: Welding

7.7.29 SMA29: xLink Robotic Arm [OSAM-2]

Description: Thee Motiv xLink robotic arm plans to 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 Space Systems
Country: United States
First Use Date: Planned for 2024
Status: In Development
Max Dimensions: "scalable"
Material Types: Metal Structure
Joining: N/A (gripper only)
Assembly Agent: Robot
Operation Regime: On-Orbit
Technology Area: Robotic Arm

7.8 Recycling, Reuse, and Repurposing

7.8.1 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: Tethers Unlimited Inc, National Aeronautics and Space Administration (NASA)
Country: United States
First Use Date: 2017

Status: Concluded
Recyclable Materials / Items: Metal
Product: Metal ingots

7.8.2 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: Cornerstone Research Group (CRG), Tethers Unlimited Inc, National Aeronautics and Space Administration (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

7.8.3 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: Tethers Unlimited Inc, National Aeronautics and Space Administration (NASA)
Country: United States
First Use Date: 2019
Status: Operational
Recyclable Materials / Items: Thermoplastic polymers
Product: Filament feedstock for 3D printing

7.8.4 RRR04: Tailored Universal Feedstock for Forming (TuFF) Reformability Demo

Description: TuFF was a small contract demonstration which expanded upon previous short fiber development work at the University of Delaware. The previous work, which was funded through a DARPA grant, was to develop repurposable fibers for composites with lower cost and aerospace grade

performance. The follow-on demonstration, TuFF, determined the requirements to reform a composite part constructed form the fibers. The demonstration produced approaches to produce 45° & 90° bends in the original structure.
Developer: University of Delaware, Composites Automation LLC
Country: United States
First Use Date: TBD
Status: Completed
Recyclable Materials / Items: Thermoplastic composites with short carbon fibers
Product: Coupons

7.8.5 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 funded through Phase 1 and Phase 2 NASA SBIRs. The project was able to demonstrate that a component can be made with a resin and then reprocessed with properties needed for structural composites. Multiple parts were created with a reformable resin and then reshaped into other parts representing potential structural parts for planetary use.
Developer: Cornerstone Research Group (CRG)
Country: United States
First Use Date: TBD
Status: In Development
Recyclable Materials / Items: Thermally reversible polymers
Product: Panels, tubes, and other geometries made with recycled composite

7.9 Parts and Goods Manufacturing

7.9.1 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 Types: Polymers/Composites
Operational Regime: On-Orbit

Operator: Human / Remote Human

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

Description: During this TDM, 55 parts of Acryonitrile Butadiene Styrene (ABS) were printed from 2014-2016. The printer operates in a Microgravity Science Glovebox (MSG).
Developer: Made In Space, National Aeronautics and Space Administration (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 Types: ABS
Operational Regime: On-Orbit (ISS)
Operator: Human / Remote Human

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

Description: The AMF is a multimaterial commercial facility for polymer printing in microgravity developed by Made in Space, Inc. The AMF was installed in the ISS EXPRESS Rack in April, 2016 and offers printing for NASA or commercial products.
Developer: Made In Space, National Aeronautics and Space Administration (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 Types: ABS, HDPE, PEI-PC initially, more upon ISS approval
Operational Regime: On-Orbit (ISS)
Operator: Human

7.9.4 PGM04: Custom Laser Doppler Sensor

Description: The Apsidal custom laser doppler sensor for real-time, in-situ analysis and feedback control during the manufacturing process. This sensor will use AI to adapt and optimize production in microgravity.
Developer: Apsidal
Country: United States
First Use Date: Planned for 2023
Status: In Development
End Product: Finished Part

Inputs: Earth Delivered Material
Max. Dimensions: Unavailable
Material Types: Glass and Glass Alloys
Operational Regime: On-Orbit (ISS)
Operator: Human / Remote Autonomous

7.9.5 PGM05: External Material Processing Platform

Description: The External Material Processing Platform is an external platform on the ISS with the capability to autonomously produce thin, metal-coated optical fibers. These fibers are expected to be useful for the medical, defense, and commercial spacecraft industries. The platform uses the vacuum and microgravity environment of space to reduce errors and defects during manufacturing.
Developer: DSTAR Communications Inc, FOMS Inc, Visioneering Space Corporation, Lunar Resources, National Aeronautics and Space Administration (NASA)
Country: United States
First Use Date: 2019
Status: Operational
End Product: Finished Part
Inputs: Earth Delivered Material
Max. Dimensions: Unavailable
Material Types: Glass and Glass Alloys
Operational Regime: On-Orbit (ISS)
Operator: Human / Remote Human

7.9.6 PGM06: Made in Space: SpaceFiber

Description: In collaboration with Thorlabs Inc., Made in Space conducted the Optical Fiber Production in Microgravity investigation on the ISS from September 2017-2018 to set the stage for large-scale manufacture of high-quality fiber optics in orbit.
Developer: Made In Space, National Aeronautics and Space Administration (NASA)
Country: United States
First Use Date: 2018
Status: Operational
End Product: Finished Part
Inputs: Earth Delivered Material
Max. Dimensions: Unavailable
Material Types: Glass and Glass Alloys
Operational Regime: On-Orbit (ISS)
Operator: Human / Remote Human

7.9.7 PGM07: Multimaterial Fabrication Laboratory [ISM]

Description: Multimaterial Fabrication Laboratory, also known as FabLab, was a Broad Agency Announcement (BAA) opportunity to develop a multimaterial printer (with a focus on metals and in-process inspection capabilities) for the ISS. 18-month phase A efforts focused on development of ground-based prototype systems and technology demonstration. There were 3 funded companies (Interlog, Tethers Unlimited, and Techshot). Techshot, now Redwire, was the only company to continue to the next phase. FabLab the 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. In 2023, Redwire was awarded a NASA contract to complete the design of the facility.
Developer: Redwire Corporation, Interlog Corporation, Tethers Unlimited Inc, National Aeronautics and Space Administration (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 Types: Metallics and Polymers
Operational Regime: On-Orbit (ISS)
Operator: Human, Remote Human, autonomous

7.9.8 PGM08: 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: National Aeronautics and Space Administration (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 Types: Polymers and Electronics
Operational Regime: On-Orbit (ISS)
Operator: Human

7.9.9 PGM09: 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 Types: Polymers/Composites
Operational Regime: On-Orbit
Operator: Human / Remote Human

7.9.10 PGM10: Orbital Fiber Optic Production Module (ORFOM)

Description: The Orbital Fiber Optic Production Module is an ISS payload designed to produce high-quality fiber optics through an automated manufacturing process. The payload, which arrived at the ISS in July of 2022, leverages the microgravity environment to avoid unwanted defects common in the terrestrial manufacturing process of fiber optics.
Developer: Mercury Systems, National Aeronautics and Space Administration (NASA)
Country: United States
First Use Date: 2022
Status: Operational
End Product: Finished Part
Inputs: Earth Delivered Material
Max. Dimensions: Unavailable
Material Types: Glass and Glass Alloys
Operational Regime: On-Orbit (ISS)
Operator: Human

7.9.11 PGM11: Redwire Regolith Print (RegISS) [ISM]

Description: RegISS is an on-orbit demonstration of 3D printing with a polymer/regolith simulant feedstock blend. It was the first demonstration of manufacturing with ISRU-derived feedstocks on ISS. This proof of concept showed 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 the Additive Manufacturing Facility was modified to accommodate a new extruder and print with a feedstock consisting of regolith simulant and a thermoplastic. The payload launched to the ISS in 2021. Sample coupons were returned to Earth and are currently undergoing analysis.
Developer: Redwire Corporation, National Aeronautics and Space Administration (NASA)
Country: United States
First Use Date: 2021
Status: Operational

End Product: Finished Part
Inputs: ISRU
Max. Dimensions: N/A (likely the size of the AMF)
Material Types: regolith simulant feedstock blend
Operational Regime: On-Orbit (ISS)
Operator: Human

7.9.12 PGM12: Sintered Inductive Metal Printer with Laser Exposure (SIMPLE) [ISM]

Description: SIMPLE was a wire-fed additive manufacturing process for metals proposed for use in space. The process used inductive heating and operated in a vacuum. A low power laser provided additional heating for the sintering process.
Developer: Redwire Corporation, National Aeronautics and Space Administration (NASA)
Country: United States
First Use Date: N/A
Status: Concluded
End Product: Finished Part
Inputs: Earth Delivered Material
Max. Dimensions: Unavailable
Material Types: Metallic
Operational Regime: Microgravity (any NASA Vehicle)
Operator: Human

7.9.13 PGM13: Vulcan [ISM]

Description: Vulcan is an in-space manufacturing facility which has the ability to produce parts form metallics, polymers, or a hybrid of materials. The facility will use additive and subtractive manufacturing processes. The additive elements are derived from wire-fed welding processes. This project started as an SBIR (phase I, II, and II-E), but has since transitioned to a contract with ISS Research Office.
Developer: Redwire Corporation, National Aeronautics and Space Administration (NASA)
Country: United States
First Use Date: N/A
Status: In Development
End Product: Finished Part
Inputs: Earth Delivered Material
Max. Dimensions: Unavailable
Material Types: Metallics and Polymers
Operational Regime: On-Orbit (ISS)
Operator: Human

7.10 Surface Construction

7.10.1 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: National Aeronautics and Space Administration (NASA)
Country: United States
First Use Date: N/A
Status: Completed
Materials (Imported v. ISRU): ISRU
Construction Agent: Robot
Auto / Fly-by-Wire / Planned: Planned

7.10.2 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, 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: National Aeronautics and Space Administration (NASA),United States 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

7.10.3 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 Ames Research Center (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

7.10.4 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 Johnson Space Center (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

7.10.5 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 advanced technology to heat the regolith to more than 3,000 degrees Fahrenheit and flow electricity through the molten material, causing a chemical reaction that splits the regolith into gaseous oxygen and metals.
Developer: NASA Kennedy Space Center (KSC)
Country: United States
First Use Date: N/A
Status: Completed
Materials (Imported v. ISRU): ISRU
Construction Agent: Robot
Auto / Fly-by-Wire / Planned: Auto

7.10.6 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. The focus of this project is landing pads.
Developer: NASA Kennedy Space Center (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

7.10.7 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 Marshall Space Flight Center (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

7.10.8 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 Kennedy Space Center (KSC)
Country: United States
First Use Date: 2008
Status: Completed
Materials (Imported v. ISRU): Imported
Construction Agent: Robot

Auto / Fly-by-Wire / Planned: Planned

7.10.9 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 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 Langley Research Center (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

7.10.10 SC10: MMPACT

Description: The Moon to Mars Planetary Autonomous Construction Technologies (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 Marshall Space Flight Center (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

7.10.11 SC11: R1

Description: The GITAI R1 is a four wheeled, robotic integrated rover which is intended to operate on the Lunar surface. The rover is capable of general-purpose tasks such as exploration, mining, inspection, maintenance, and assembly. The rover is integrated with two robotic arms with generic gripper end effectors to allow for general purpose use. This rover has been tested in a simulated lunar environment at JAXA's Sagamihara Campus. In March 2023, a demonstration of cooperative lunar base construction using two GITAI inchworm-type robotic arms and two GITAI Lunar Robotic Rovers was successfully completed in a simulated lunar environment. By cooperation with inchworm-type robotic arm, self-repairing (e.g. changing the rover tire) is available as well.
Developer: GITAI
Country: Japan

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

7.10.12 SC12: RASSOR
Description: The Regolith Advanced Surface Systems Operations Robot (RASSOR) Excavator 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 Kennedy Space Center (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

7.10.13 SC13: 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 Kennedy Space Center (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

7.10.14 SC14: Redwire Regolith Print (RegISS) [ISM]
Description: RegISS is an on-orbit demonstration of 3D printing with a polymer/regolith simulant feedstock blend. It was the first demonstration of manufacturing with ISRU-derived feedstocks on ISS. This proof of concept showed 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 the Additive Manufacturing Facility was modified to accommodate a new extruder and print with a feedstock consisting of regolith simulant and a thermoplastic. The payload launched to the ISS in 2021. Sample coupons were returned to Earth and are currently undergoing analysis.
Developer: Made In Space, National Aeronautics and Space Administration (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

7.10.15 SC15: Tall Lunar Tower (TLT)

Description: Tall Lunar Tower (TLT) is a Project Polaris activity from NASA's ESDMD to demonstrate assembly of a large tower. These towers could be assembled on planetary surfaces to support solar arrays, communications antenna, and navigation beacons. An assembly demonstration of an engineering development unit is planned for August 2023 at NASA Langley Research Center.
Developer: NASA Langley Research Center (LaRC)
Country: United States
First Use Date: TBD
Status: In Development
Materials (Imported v. ISRU): Imported
Construction Agent: Robot
Auto / Fly-by-Wire / Planned: Unavailable

7.11 Inspection and Metrology

7.11.1 IM01: AeroCube-10 (AC-10)

Description: AeroCube-10 is a 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

7.11.2 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: United States Department of Energy (DOE),National Aeronautics and Space Administration (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

7.11.3 IM03: Automated Navigation and Guidance Experiment for Local Space (ANGELS)

Description: Automated Navigation and Guidance Experiment for Local Space (ANGELS) evaluates space situational awareness 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. ANGELS uses ground commanded authorization to proceed at setpoints throughout the experiment.
Developer: Air Force Research Laboratory (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

7.11.4 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: National Aeronautics and Space Administration (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

7.11.5 IM05: Laura

Description: Laura is a satellite for inspection and monitoring through cameras and sensors. The satellite also has multispectral capabilities to allow for inspection without making physical contact.
Developer: Rogue Space Systems Corporation
Country: United States
First Use Date: Planned for Q4 2023
Status: In Development
Contact: N, free-flying
Inspection Type: Visual
Resolution: High
Inspection Aides / Fiducials / Cues: Multispectral sensor capabilities
Data Analysis: Off-board

7.11.6 IM06: Mission Extension Vehicle (MEV)

Description: The Mission Extension Vehicle (MEV) is the first commercial 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: 2020-02-25
Status: Operational
Contact: Y
Inspection Type: Unavailable
Resolution: Unavailable
Inspection Aides / Fiducials / Cues: Unavailable
Data Analysis: Unavailable

7.11.7 IM07: Mission Robotic Vehicle (MRV) [RSGS]

Description: Mission Robotic Vehicle is 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: Northrop Grumman
Country: United States
First Use Date: TBD
Status: In Development
Contact: Unavailable
Inspection Type: Unavailable
Resolution: Unavailable
Inspection Aides / Fiducials / Cues: Unavailable
Data Analysis: Unavailable

7.11.8 IM08: Mycroft

Description: Mycroft is a 4th-generation experimental Space Situational Awareness (SSA) spacecraft that builds upon technology, knowledge, and lessons learned from XSS-10, XSS-11, and ANGELS. The mission is exploring ways to enhance space object characterization by evaluating the region around EAGLE using an SSA camera, and it uses sensors and software to perform advanced guidance, navigation, and control functions.
Developer: Air Force Research Laboratory (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

7.11.9 IM09: NASA Langley's Extravehicular Activity (EVA) Infrared Camera

Description: NASA Langley's EVA IR camera was a tool developed to detect subsurface damage to the reinforced carbon-carbon structures of the space shuttle. The camera was first demonstrated during the third EVA of STS-121.
Developer: National Aeronautics and Space Administration (NASA)
Country: United States
First Use Date: 2006
Status: Completed
Contact: Y, robot-arm
Inspection Type: Visual
Resolution: Unavailable

Inspection Aides / Fiducials / Cues: Unavailable
Data Analysis: Off-board

7.11.10 IM10: Orbital Express

Description: Launched March 8, 2007 as part of the United States Air Force Space Test 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: Defense Advanced Research Projects Agency (DARPA), National Aeronautics and Space Administration (NASA)
Country: United States
First Use Date: 2007
Status: Completed
Contact: Y, robot-arm
Inspection Type: Visual
Resolution: Unavailable
Inspection Aides / Fiducials / Cues: GPS, ADCS, Ground Station comms
Data Analysis: Unavailable

7.11.11 IM11: OSAM-1

Description: OSAM-1 is a spacecraft under development by NASA and Maxar which will demonstrate activities required for unplanned satellite mission extension. OSAM-1 will rendezvous with and refuel Landsat 7, which will require activities such as cutting insulation, unscrewing bolts and caps, and attaching propellant lines. After completing refuel of Landsat 7, the hosted SPIDER payload will assemble a communications antenna.
Developer: National Aeronautics and Space Administration (NASA), Maxar Technologies
Country: United States
First Use Date: Planned for 2025
Status: In Development
Contact: Y
Inspection Type: Visual
Resolution: Unavailable
Inspection Aides / Fiducials / Cues: Unavailable
Data Analysis: Unavailable

7.11.12 IM12: Programmable Josephson Voltage Standard (PJVS)

Description: The Programmable Josephson Voltage Standard is an intrinsic electrical DC Voltage Standard used internationally by national measurement institutes. 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), National Aeronautics and Space Administration (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

7.11.13 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 Goddard Space Flight Center (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

7.11.14 IM14: SCOUT
Description: SCOUT helps SpaceCraft Observe and Understand Things around them. The software suite enables on-demand, on-site inspections for space assets.
Developer: SCOUT Space Inc
Country: United States
First Use Date: 2021-06-01
Status: Completed
Contact: N, free-flying
Inspection Type: Visual
Resolution: High
Inspection Aides / Fiducials / Cues: Stereoscopic and Multispectral configurations
Data Analysis: Autonomous

7.11.15 IM15: Seeker [ISS]

Description: Seeker was a 3U spacecraft which was deployed from Orbital ATK Enhanced Cygnus ISS resupply spacecraft. The CubeSat completed a 60-minute mission consisting of proximity operations around Cygnus. UT-developed vision systems, which were isolated from all other sensors onboard the spacecraft, used a commercially available camera and state-of-the-art computer vision algorithms to detect the Cygnus spacecraft.
Developer: The University of Texas at Austin (UT Austin), NASA Johnson Space Center (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)

7.11.16 IM16: Sonatest Veo PAUT [ISS]

Description: The Sonatest Veo PAUT is a phased array ultrasonic test (PAUT) device which can assess the body of the ISS following a micrometeoroid strike. By making contact between the device and the area of damage, the device is able to find hidden structures such as isogrid webs. This detection method allows a repair team to determine what type of repair is required.
Developer: National Aeronautics and Space Administration (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

7.11.17 IM17: Soul

Description: SOUL is a tethered robotic spacecraft that is designed to provide self-inspection and self-servicing to a client spacecraft. The tethered spacecraft is less than 10 kg, self-propelled, self-navigating, and autonomous. Power and commands are supplied by the host spacecraft.
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

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

Description: VIPIR, the Visual Inspection Poseable Invertebrate Robot, was a robotic, multi-capability inspection tool designed to deliver near and midrange inspection capabilities in space. This robot was used on RRM2.
Developer: NASA Goddard Space Flight Center (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

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

Description: VIPR2 was robotic inspection camera used to visually verify entry and positioning of the flexible Cryogen Transfer Hose (CTH) into the receiver tank. VIPR2 was used on RRM3.
Developer: NASA Goddard Space Flight Center (GSFC)
Country: United States
First Use Date: 2018-12-08 00:00:00
Status: Completed
Contact: Y
Inspection Type: Visual
Resolution: Unavailable
Inspection Aides / Fiducials / Cues: Unavailable
Data Analysis: Off-board

7.11.20 IM20: XSS-10

Description: eXperimental Small Satellite 10 (XSS-10) was a micro-satellite with objectives to demonstrate autonomous navigation, proximity operations, and inspection of another space object. The satellite was launched and completed operations, including the imaging of a Delta II upper stage, in 2003.
Developer: Air Force Research Laboratory (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

7.11.21 IM21: XSS-11

Description: eXperimental Small Satellite 11 (XSS-11) was a micro-satellite demonstrating rendezvous and proximity operations with expended rocket body. The satellite conducted proximity maneuvers with several US-owned, dead, or inactive resident space objects near its orbit.
Developer: Air Force Research Laboratory (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

8 Appendix – ISAM Developers

8.1 AI SpaceFactory

Description: AI SpaceFactory is a construction technology company specializing in the design and construction of habitats on planetary bodies. It develops advanced construction technologies for space exploration using autonomous robotics and sustainable materials.
Country: United States
Type: Industry
Year Founded: 2017
URL: https://www.aispacefactory.com/
State of Play Entries: SC13

8.2 Air Force Research Laboratory (AFRL)

Description: The Air Force Research Laboratory (ARFL) is a government research laboratory performing research and development for the U.S. Air Force and the U.S. Space Force. Its main purpose is to develop and deliver warfighting technologies to the U.S air, space, and cyberspace forces by conducting cutting-edge research in various areas of science and technology, including aerospace systems, robotics, directed energy, communication systems, artificial intelligence, and materials science.
Country: United States
Type: Government
Year Founded: 1997
URL: https://www.afrl.af.mil/
State of Play Entries: RCDM03, RCDM17, RCDM36, RCDM37, IM03, IM08, IM20, IM21

8.3 Airbus Defense and Space Netherlands (ADSN)

Description: Airbus Defense and Space Netherlands (ADSN) is an aerospace and defense company specializing in solar arrays, satellite instrumentation and structures, and satellite intelligence. Its current developments include laser communications, articulated deployment systems, and secondary payload structures.
Country: Netherlands
Type: Government
Year Founded: 1968
URL: http://www.dutchspace.nl
State of Play Entries: RM07

8.4 Altius Space Machines Inc

Description: Altius Space Machines is a space technology company specializing in satellite servicing, satellite end-of-life services, and orbital debris mitigation technologies. Its scope of operations encompasses rendezvous and capture devices, spacecraft mechanisms, in-space propellant transfer, and

other satellite servicing technologies.
Country: United States
Type: Industry
Year Founded: 2010
URL: https://altius-space.com/
State of Play Entries: PRUMI02, PRUMI08

8.5 Apsidal

Description: Apsidal is a computing and manufacturing technology company focused on photonics and quantum information solutions. Its developments include AI-enhanced photonics manufacturing processes and optical technologies for quantum applications.
Country: United States
Type: Industry
Year Founded: 2019
URL: http://apsidal.net/
State of Play Entries: PGM04

8.6 Astroscale

Description: Astroscale is a space technology company specializing in on-orbit servicing and mitigation of space debris. It develops and deploys technologies and spacecraft to perform life extension, end-of-life disposal, and active debris removal.
Country: Japan
Type: Industry
Year Founded: 2013
URL: https://astroscale.com/
State of Play Entries: RCDM01, RCDM08, RCDM09, RCDM10, R02

8.7 Busek Co. Inc

Description: Busek Co. Inc. is a space propulsion technology company specializing in the design and development of electric propulsion systems. Busek designs and develops Hall thrusters, electrospray thrusters, and ion thrusters for applications including satellite station keeping, orbit transfers, and interplanetary missions.
Country: United States
Type: Industry
Year Founded: 1985
URL: https://www.busek.com/
State of Play Entries: RCDM33, PRUMI17, IM17

8.8 Canadian Space Agency (CSA)

Description: The Canadian Space Agency (CSA) is the national space agency of Canada. Its main purpose is to advance the knowledge of space through science and ensure social and economic benefits for Canadians. It has developed several robotic manipulation systems to support human exploration.
Country: Canada
Type: Government
Year Founded: 1989
URL: https://www.asc-csa.gc.ca/eng/
State of Play Entries: RM03, RM04, RM05

8.9 China Academy of Space Technology (CAST)

Description: The China Academy of Space Technology (CAST) is a spacecraft development organization within the China Aerospace Science and Technology Corporation (CASC).
Country: China
Type: Government
Year Founded: 1968
URL: https://www.cast.cn/english
State of Play Entries: RCDM32

8.10 Composites Automation LLC

Description: Composites Automation LLC is a composite manufacturing technology company specializing in novel composite manufacturing materials, design, and processes. Its scope of developments includes unique composite processing, analytical, and finite element design capabilities.
Country: United States
Type: Industry
Year Founded: 2001
URL: https://www.compositesautomationllc.com/
State of Play Entries: RRR04

8.11 Cornerstone Research Group (CRG)

Description: Cornerstone Research Group (CRG) is an aerospace and defense firm providing research and development of advanced materials and technology solutions for various industries including aerospace, defense, energy, and transportation.
Country: United States
Type: Industry
Year Founded: 1997
URL: https://www.crgrp.com/
State of Play Entries: RRR02, RRR05

8.12 Defense Advanced Research Projects Agency (DARPA)

Description: The Defense Advanced Research Projects Agency (DARPA) is a research and development agency of the U.S. Department of Defense tasked with the development of new technologies for use by the military. Its main purpose is to make investments in breakthrough technologies for national security, including autonomous vehicles, stealth technology, directed energy, artificial intelligence, robotics, and other domains.
Country: United States
Type: Government
Year Founded: 1958
URL: https://www.darpa.mil/
State of Play Entries: RM08, RM21, RCDM20, PRUMI09, RFT11, IM10

8.13 D-Orbit

Description: D-Orbit is an aerospace company specializing in orbital transportation and space logistics. Its scope of operations includes orbital transportation and end-of-mission disposal. Its developments include mission control software, space cloud computing, and an orbital transfer vehicle.
Country: Italy
Type: Industry
Year Founded: 2011
URL: https://www.dorbit.space/
State of Play Entries: R03

8.14 DSTAR Communications Inc

Description: DSTAR Communications Inc is an optical materials technology company. Its developments include biomedical photonics technologies for life sciences, integrated laser subsystems, and an external material processing platform on the International Space Station with autonomous, high throughput manufacturing capability.
Country: United States
Type: Industry
Year Founded: 2018
URL: https://dstarcom.com/
State of Play Entries: PGM05

8.15 Eta Space

Description: Eta Space is an aerospace company specializing in technology for cryogenic fluid management and chemical propulsion systems. The company is currently developing technologies related to refrigeration and storage, liquid hydrogen testing, in-space propellant depots, cryocooler development, zero loss propellant storage and transfer, and ISRU and cryogenic liquefaction.
Country: United States
Type: Industry

Year Founded: 2019
URL: https://etaspace.com/
State of Play Entries: RFT09

8.16 European Space Agency (ESA)

Description: The European Space Agency (ESA) is an intergovernmental space organization with a mission to shape the development of Europe's space capability and ensure that investment in space continues to deliver benefits to the citizens of Europe and the world. The agency's work is focused on implementing European space policy, enacting activities and programs in the space field, and coordinating the European space program, national programs, and industry activities.
Country: Multinational
Type: Government
Year Founded: 1975
URL: https://www.esa.int/
State of Play Entries: RCDM13, PRUMI18, RFT14

8.17 Firefly Aerospace

Description: Firefly Aerospace is an aerospace company specializing in the launch, landing, and in-space operation of space systems. Its current developments include the production of small-lift launch vehicles, the design and deployment of lunar landers, and the operation of surface mobility vehicles.
Country: United States
Type: Industry
Year Founded: 2017
URL: https://fireflyspace.com/
State of Play Entries: R15

8.18 FOMS Inc

Description: FOMS Inc, or Fiber Optic Manufacturing in Space Inc, is a space technology company focused on the in-space manufacturing of optical fibers. FOMS is currently developing equipment for the fabrication of specialty optical fibers on the International Space Station.
Country: United States
Type: Industry
Year Founded: 2019
URL: https://fomsinc.com/
State of Play Entries: PGM05

8.19 General Motors

Description: General Motors is a multinational automotive manufacturing company specializing in automobiles and trucks, automotive components, and engines. Its space-related developments include robotic manipulation systems.

Country: United States
Type: Industry
Year Founded: 1908
URL: https://www.gm.com/
State of Play Entries: RM25

8.20 German Space Agency (GSA)

Description: The German Space Agency at the German Aerospace Center (DLR), (formerly DLR Space Administration) is the national space agency of Germany. Its main purpose is the planning and implementation of the German national space program and the management of Germany's contributions to the European Space Agency (ESA) and the European Organization for the Exploitation of Meteorological Satellites (EUMETSAT).
Country: Germany
Type: Government
Year Founded: 1969
URL: https://www.dlr.de/en
State of Play Entries: PRUMI06

8.21 GITAI

Description: GITAI is a robotics company specializing in the design and development of robotic systems for space construction and maintenance applications. Its systems support teleoperability and autonomous robotic manipulation and its developments include lunar rovers and robotic manipulators for satellite, terrestrial, and space station applications.
Country: United States
Type: Industry
Year Founded: 2016
URL: https://gitai.tech/
State of Play Entries: RM09, RM26, RM27, RM28, PRUMI07, SMA09, SC11

8.22 ICON

Description: ICON is an architecture and construction technology company specializing in 3D printing and advanced materials. Its developments include the design of 3D printed space habitats to support the future exploration of the Moon and lunar surface construction technologies.
Country: United States
Type: Industry
Year Founded: 2017
URL: https://www.iconbuild.com/
State of Play Entries: SC10

8.23 Interlog Corporation

Description: Interlog Corporation is an electrical and mechanical manufacturing company specializing in the fabrication of military and commercial electronic components. Its developments include vehicular lights, signal components, electrical assemblies, wiring harnesses, and other precision-fabricated components.
Country: United States
Type: Industry
Year Founded: 1992
URL: https://interlogcorp.com/
State of Play Entries: PGM07

8.24 Japan Aerospace Exploration Agency (JAXA)

Description: The Japan Aerospace Exploration Agency (JAXA) or National Research and Development Agency Aerospace Research and Development Organization is the Japanese national air and space agency. It is designated as a core performance agency to support the Japanese government's overall aerospace development and utilization. Its scope of operations includes integrated operations from basic research and development to utilization.
Country: Japan
Type: Government
Year Founded: 2003
URL: https://global.jaxa.jp/
State of Play Entries: RM11, RM12, RCDM01, RCDM11

8.25 Launcher Space

Description: Launcher Space was an aerospace company which specialized in the development of rockets and transfer vehicles to deliver small satellites to orbit. Its scope of developments included liquid propulsion technology and onsite 3D manufacturing for high-efficiency engines. Launcher Space was acquired by Vast in 2023.
Country: United States
Type: Industry
Year Founded: 2017
URL: https://www.launcherspace.com/
State of Play Entries: R09

8.26 LERA

Description: LERA Consulting Structural Engineers is a structural engineering firm specializing in structural design. The company's areas of expertise include structural designs, feasibility studies, peer reviews, value engineering, computational design, blast analysis and design, forensic consulting, and special inspections.
Country: United States

Type: Industry
Year Founded: 1923
URL: https://www.lera.com/
State of Play Entries: SC13

8.27 Lockheed Martin

Description: The Lockheed Martin Corporation is an aerospace, arms, defense, information security, and technology corporation specializing in Aeronautics, Missiles and Fire Control (MFC), Rotary and Mission Systems (RMS), and Space. Its developments include the Orion spacecraft command module and hydrogen fluid management systems.
Country: United States
Type: Industry
Year Founded: 1995
URL: https://www.lockheedmartin.com/
State of Play Entries: RFT09

8.28 Lunar Resources Inc

Description: Lunar Resources Inc is a space technology company focusing on in-space manufacturing and resource extraction. Its prospective developments include in-situ construction of lunar infrastructure such as a radio observatory, photovoltaic power grid, and regolith additive manufacturing.
Country: United States
Type: Industry
Year Founded: 2019
URL: https://www.lunarresources.space/
State of Play Entries: PGM05

8.29 Made In Space

Description: Made In Space was an aerospace company specialized in commercial additive manufacturing in microgravity. The company was acquired by Redwire Corporation in 2020.
Country: United States
Type: Industry
Year Founded: 2010
URL: http://madeinspace.us/
State of Play Entries: PGM02, PGM03, PGM06, SC14

8.30 Martin Marietta Corporation

Description: The Martin Marietta Corporation was an aerospace company specialized in missile technology. Its developments included the Titan program, the Viking program, and the space shuttle external tank. In 1995, it merged with Lockheed Corporation to form the Lockheed Martin Corporation.
Country: United States

Type: Industry
Year Founded: 1961
URL: N/A
State of Play Entries: RFT19

8.31 Maxar Technologies

Description: Maxar Technologies is a space technology company specializing in manufacturing communication, Earth observation, radar, and on-orbit satellite servicing. Its developments include the Power and Propulsion Element for the Lunar Gateway, 3D geospatial analytics, satellite imagery, analytics, and data modeling.
Country: United States
Type: Industry
Year Founded: 2017
URL: https://www.maxar.com/
State of Play Entries: RM10, RM15, RM16, RM22, RM23, RM30, RCDM21, ULRM04, SMA22, IM11

8.32 Maxon Group

Description: Maxon Group is an electronic manufacturer of high precision motor systems. Its developments include electric AC motors, DC motors, encoders, gears, motor controllers, and sensors for applications within the aerospace, automotive, communication, industrial automation, measuring and testing, medical, and security technology industries.
Country: Switzerland
Type: Industry
Year Founded: 1961
URL: https://www.maxongroup.com/
State of Play Entries: RCDM13

8.33 MDA Space

Description: MDA Space is a space technology company specializing in robotics, satellite technology, and satellite operations. Its developments include the Mobile Servicing System for the International Space Station, which includes Canadarm2, and the Canadarm3 for the Lunar Gateway.
Country: Canada
Type: Industry
Year Founded: 1968
URL: https://mda.space/
State of Play Entries: RM03, RM04, RM05, RM10, RM15, RM16, RM21, RM22, RM23

8.34 Mercury Systems

Description: Mercury Systems is a technology company focused on aerospace and defense applications. Its developments include electronic warfare development systems, communications and networking

technologies, sensors and scanners, military rugged display systems, rugged servers and subsystems, computer boards, and microelectronic components.
Country: United States
Type: Industry
Year Founded: 1981
URL: https://www.mrcy.com/company
State of Play Entries: PGM10

8.35 Momentus Inc

Description: Momentus Space is a spaceflight company specializing in on-orbit servicing of space infrastructure and propulsion systems. Its developments include in-space transportation and orbit transfer technologies, and water plasma-based propulsion systems in the form of Microwave Electrothermal Thruster (MET) propulsion technology.
Country: United States
Type: Industry
Year Founded: 2017
URL: https://investors.momentus.space/
State of Play Entries: R16

8.36 MOOG

Description: Moog is an electromechanical technology company specializing in precision motion control systems. Its developments include actuators, motion controllers, rotary joints, and motors for robotic systems.
Country: United States
Type: Industry
Year Founded: 1953
URL: https://www.moog.com/
State of Play Entries: RM08, RCDM18, R08, RFT08

8.37 Motiv Space Systems

Description: Motiv Space Systems is a robotics company specializing in robotic arm systems for use in space or on planetary surfaces. Its developments include the xLink Robotic arm for the OSAM-2 demonstration mission and the robotic arm for the NASA JPL 2020 Mars Perseverance Rover.
Country: United States
Type: Industry
Year Founded: 2014
URL: https://motivss.com/
State of Play Entries: RM34, SMA28

8.38 NASA Ames Research Center (ARC)

Description: NASA's Ames Research Center (ARC) conducts research and development activities in aeronautics, space exploration, space technology, and science. ARC was the second NACA laboratory founded to conduct research on early aircraft, and now provides expertise in space domains such as small satellite technologies, supercomputing, intelligent robotics, planetary science, and other research areas.
Country: United States
Type: Government
Year Founded: 1939
URL: https://www.nasa.gov/ames
State of Play Entries: RM19, RM29, SC03

8.39 NASA Goddard Space Flight Center (GSFC)

Description: NASA's Goddard Space Flight Center (GSFC) is a research, development, and operations center focused on increasing the scientific understanding of the Earth, Solar System, and universe. GSFC operates many NASA science missions, including the Hubble Space Telescope and James Webb Space Telescope, operates satellite tracking networks, and supports many NASA and international spacecraft and missions.
Country: United States
Type: Government
Year Founded: 1959
URL: https://www.nasa.gov/goddard
State of Play Entries: RCDM06, RCDM25, RFT16, IM13, IM18, IM19

8.40 NASA Jet Propulsion Laboratory (JPL)

Description: NASA's Jet Propulsion Laboratory (JPL) is a federally funded research and development center (FFRDC) managed by Caltech. JPL's core capability is to integrate science, engineering, and technology to provide end-to-end implementation of robotic space missions. JPL is responsible for developing NASA's Mars rovers and other robotic science missions, operating the Deep Space network, and research and development of other space technology.
Country: United States
Type: Government
Year Founded: 1936
URL: https://www.jpl.nasa.gov/
State of Play Entries: RM17

8.41 NASA Johnson Space Center (JSC)

Description: NASA's Johnson Space Center (JSC)'s is the lead center for human space exploration, training the agency's astronaut corps, running International Space Station (ISS) mission operations, and advancing other human exploration capabilities. JSC has led NASA's human exploration missions

including Apollo, Space Shuttle, and ISS, and Artemis development, and performs research and development of several human spaceflight technologies.
Country: United States
Type: Government
Year Founded: 1961
URL: https://www.nasa.gov/centers/johnson/home/index.html
State of Play Entries: RFT12, SC04, IM15

8.42 NASA Kennedy Space Center (KSC)

Description: NASA's Kennedy Space Center (KSC) serves as NASA's launch facility, and it also performs research in several areas related to humans living and working on planetary bodies. The center supports commercial launches and provides facilities for a number of commercial launch companies to run their launch operations.
Country: United States
Type: Government
Year Founded: 1962
URL: https://www.nasa.gov/centers/kennedy/home/index.html
State of Play Entries: SC05, SC06, SC08, SC12, SC13

8.43 NASA Langley Research Center (LaRC)

Description: NASA's Langley Research Center (LaRC) is the nation's first civilian aeronautics research and development laboratory, and today supports aeronautics, science, and space missions. The research at LaRC provides improvements to aviation, expands understanding of Earth's atmosphere, develops technology for space exploration, and analyzes new system concepts.
Country: United States
Type: Government
Year Founded: 1917
URL: https://www.nasa.gov/langley
State of Play Entries: RM01, RM14, RM33, SMA03, SMA26, SC09, SC15

8.44 NASA Marshall Space Flight Center (MSFC)

Description: NASA Marshall Space Flight Center (MSFC), located in Huntsville, Alabama, is a leader in design, development, and test and evaluation with an emphasis on technology and system development for human exploration. NASA MSFC also has a rich history of science for robotic missions and is home to NASA's Planetary Missions Program Office.

Country: United States
Type: Government
Year Founded: 1960
URL: https://www.nasa.gov/centers/marshall/home/index.html
State of Play Entries: RFT03, RFT04, SMA14, SC07, SC10

8.45 National Aeronautics and Space Administration (NASA)

Description: The National Aeronautics and Space Administration (NASA) is America's civil space program with an emphasis on human exploration, space science (Earth science, planetary science, heliophysics, biological and physical science, and astrophysics), and advancement in space technology. NASA performs these activities at 20 centers and facilities across the U.S. and the International Space Station.
Country: United States
Type: Government
Year Founded: 1958
URL: https://www.nasa.gov/
State of Play Entries: RM15, RM18, RM20, RM25, RCDM12, RCDM18, RCDM20, RCDM21, RCDM27, RCDM28, RCDM29, RCDM30, RCDM31, R04, R11, R12, R13, PRUMI09, PRUMI10, PRUMI11, PRUMI12, PRUMI13, PRUMI14, PRUMI15, ULRM04, ULRM05, ULRM06, ULRM07, ULRM08, RFT01, RFT02, RFT06, RFT07, RFT08, RFT09, RFT10, RFT11, RFT13, RFT15, RFT17, RFT20, SMA01, SMA02, SMA04, SMA05, SMA07, SMA08, SMA10, SMA13, SMA15, SMA16, SMA19, SMA20, SMA24, SMA25, RRR01, RRR02, RRR03, PGM02, PGM03, PGM05, PGM06, PGM07, PGM08, PGM10, PGM11, PGM12, PGM13, SC01, SC02, SC14, IM02, IM04, IM09, IM10, IM11, IM12, IM16

8.46 National Institute of Standards and Technology (NIST)

Description: The National Institute of Standards and Technology (NIST) is a U.S. government agency under the Department of Commerce. Its mission is to promote U.S. innovation and industrial competitiveness by advancing measurement science, standards, and technology.
Country: United States
Type: Government
Year Founded: 1901
URL: https://www.nist.gov/
State of Play Entries: IM12

8.47 National Space Development Agency of Japan (NASDA)

Description: The National Space Development Agency of Japan (NASDA) was a Japanese national space agency responsible for developing, launching, and tracking satellites. It also developed and operated the N-I, N-II, and H-I launch vehicles. In 2003, NASDA merged with the Institute of Space and Astronautical Science (ISAS) and the National Aerospace Laboratory of Japan (NAL) to become the Japan Aerospace Exploration Agency (JAXA).
Country: Japan
Type: Government
Year Founded: 1969
URL: N/A
State of Play Entries: RM06

8.48 National University of Defense Technology (NUDT)

Description: The National University of Defense Technology (NUDT) was founded as China's People's Liberation Army (PLA) Military Academy of Engineering, or Harbin Military Academy of Engineering. Its disciplines cover eight categories, including science, engineering, military science, management, philosophy, economics, law, and literature.
Country: China
Type: Government
Year Founded: 1953
URL: https://english.nudt.edu.cn/
State of Play Entries: RCDM04, R01, RFT22

8.49 Naval Research Laboratory (NRL)

Description: The Naval Research Laboratory (NRL) is a research and engineering lab which advances technology for the US Navy and US Marine Corps. The NRL conducts a broad program of scientific research and advanced technology development. NRL's scientists and engineers conduct basic and applied research across a wide spectrum of scientific disciplines for both immediate and long-range national defense needs. NRL's research is primarily sponsored by government agencies including the Office of Naval Research, Naval Systems Commands and Warfare Centers, Air Force, Army, DARPA, Department of Energy, and NASA.
Country: United States
Type: Government
Year Founded: 1923
URL: https://www.nrl.navy.mil/
State of Play Entries: RM08

8.50 North American Rockwell

Description: North American Rockwell was a corporation formed by the acquisition and merger of the Rockwell Standard with North American Aviation. Its main developments included the Apollo command and service module and the Apollo-Soyuz Test Project Docking Module.
Country: United States
Type: Industry
Year Founded: 1967
URL: N/A
State of Play Entries: RCDM07

8.51 Northrop Grumman

Description: Northrop Grumman is a global aerospace, defense and security company that serves as a major contractor of the U.S. government. As part of its Space Systems sector, Northrop Grumman designed and built the Mission Extension Vehicle to provide life extension services to GEO satellites.
Country: United States

Type: Industry
Year Founded: 1994
URL: https://www.northropgrumman.com/
State of Play Entries: RCDM15, RCDM16, R05, R06, R07, ULRM02, ULRM03, IM06, IM07

8.52 NovaWurks

Description: NovaWurks is an aerospace company specializing in small satellite technologies. Its developments include integrated small satellites for the DARPA Phoenix project.
Country: United States
Type: Industry
Year Founded: 2011
URL: https://www.novawurks.com/
State of Play Entries: PRUMI16, RFT18, SMA21

8.53 Obruta Space Solutions

Description: Obruta Space Solutions is an aerospace company specializing in rendezvous, proximity operations, and docking systems and orbital logistics. Its developments include debris removal technologies and on-orbit servicing technologies.
Country: Canada
Type: Industry
Year Founded: 2016
URL: https://www.obruta.com/
State of Play Entries: PRUMI19

8.54 Oceaneering International Inc

Description: Oceaneering International Inc is a marine engineering company that provides engineered services and hardware to marine and space operations. It has developed multiple technologies and systems for commercial and government undersea operations. Some of those technologies and capabilities translated to space, including space suits, interfaces, and robotics.
Country: United States
Type: Industry
Year Founded: 1964
URL: https://www.oceaneering.com/
State of Play Entries: PRUMI04

8.55 Orbit Fab

Description: Orbit Fab is an aerospace company specializing in in-space fuel transfer and storage. Its developments include in-orbit fuel depot satellites, fluid transfer interfaces, and mission analysis software.
Country: United States

Type: Industry
Year Founded: 2018
URL: https://www.orbitfab.com/
State of Play Entries: RCDM35, RFT05, RFT21

8.56 Orbital Composites

Description: Orbital Composites is an additive manufacturing company specializing in robotic 3D printing and composites manufacturing. Its developments include orbital manufacturing and assembly, thermal protection systems, GEO and cis-Lunar optical Imaging, and communication satellites.
Country: United States
Type: Industry
Year Founded: 2014
URL: https://www.orbitalcomposites.com/
State of Play Entries: PGM01, PGM09

8.57 People's Liberation Army (PLA)

Description: The People's Liberation Army (PLA) is the military for the People's Republic of China. The PLA has a space program that supports China's military operations, providing reconnaissance, navigation, communication, and other functions.
Country: China
Type: Government
Year Founded: 1927
URL: N/A
State of Play Entries: RCDM04, R01

8.58 QinetiQ Space

Description: QinetiQ Space is an aerospace company specializing in design, integration, test, and training for space infrastructure and other mission systems. It operates in a number of areas, including secure communications and position, navigation, and timing. QinetiQ Space was acquired by Redwire Corporation in 2022.
Country: Multinational
Type: Industry
Year Founded: 2001
URL: https://www.qinetiq.com/en/markets/space
State of Play Entries: RCDM13

8.59 Redwire Corporation

Description: Redwire is an aerospace company specializing in in-space manufacturing and infrastructure technologies. Its developments include solar arrays and deployable structures, microgravity manufacturing technologies, RF systems and satellite payloads, digital engineering, modeling, and

simulation tools.
Country: United States
Type: Industry
Year Founded: 2020
URL: https://redwirespace.com/
State of Play Entries: RM31, SMA06, SMA14, PGM07, PGM11, PGM12, PGM13

8.60 RKK Energiya

Description: Energia Corporation, formerly RKK "Energiya", NPO Energia,
TsKBEM, and OKB-1 is a Russian space company specializing in the production of spaceflight components. The company was founded in 1946 and was responsible for the construction of the Sputnik 1 artificial satellite. Its current developments include the Russian Soyuz MS spacecraft, the Russian Orbital Segment of the ISS, the Sea Launch project, and the Universal Spacecraft Configuration for use on satellites.
Country: Russia
Type: Industry
Year Founded: 1946
URL: http://www.energia.ru/ru/corporation/corporation.html
State of Play Entries: RCDM05

8.61 Rogue Space Systems Corporation

Description: Rogue Space Systems Corporation is an aerospace company specializing in satellite design and on-orbit servicing. Its operations include designing satellite vehicles and subsystems to provide on-orbit services to satellite operators.
Country: United States
Type: Industry
Year Founded: 2020
URL: https://rogue.space/
State of Play Entries: IM05

8.62 Roscosmos

Description: Roscosmos is a Russian state-run corporation responsible for operating the Russian state space program. Roscosmos was founded in 1992 after the dissolution of the USSR. The state-run company is responsible for conducting research, maintaining the Russian space flight program, and partnering with other countries in the operation of the ISS.
Country: Russia
Type: Government
Year Founded: 1992
URL: http://www.roscosmos.ru/
State of Play Entries: R04, RFT14

8.63 RUAG

Description: RUAG is an aerospace company specializing in military and commercial aerospace technologies. Its developments include information and communication systems, small-caliber ammunition, as well as aircraft and rotorcraft servicing.
Country: Switzerland
Type: Industry
Year Founded: 1999
URL: https://www.ruag.com/en
State of Play Entries: RCDM13

8.64 RUSSIA

Description: Russia is a Eurasian country which was founded in the early 1990s after the dissolution of the USSR. The country is the largest in the world by area and hosts approximately 144 million people. The country is a cooperative partner in the operation of the ISS and maintains its own space program.
Country: Russia
Type: Government
Year Founded: 1991
URL: http://government.ru/en/
State of Play Entries: RM32

8.65 SCOUT SPACE INC

Description: SCOUT Space is an aerospace company specializing in autonomy and inspection technologies for the space industry. Its developments include in-space observation, digital twin environments, space traffic management, and proximity operations.
Country: United States
Type: Industry
Year Founded: 2019
URL: https://www.scout.space/
State of Play Entries: RCDM26, IM14

8.66 SENER

Description: SENER is an international engineering firm specializing in the aerospace, civil, and energy sectors. Its developments include electromechanical systems, antennas and RF equipment, guidance, navigation and control systems, and space-grade power electronics.
Country: Spain
Type: Industry
Year Founded: 1967
URL: https://www.group.sener/
State of Play Entries: RCDM13

8.67 Sierra Nevada Corporation

Description: Sierra Nevada Corporation is an aerospace company specializing in aerospace, security and defense technologies. The company offers technical solutions for spacecraft, aircraft, and cybersecurity to government and industry customers. Its developments include aircraft modification, intelligence, surveillance technologies, electromagnetic spectrum operational capabilities, and joint all-domain command and control (JADC2).
Country: United States
Type: Industry
Year Founded: 1963
URL: https://www.sncorp.com/
State of Play Entries: RCDM13

8.68 Space Applications Services

Description: Space Applications Services is an aerospace company specializing in aerospace technology solutions in the fields of spacecraft, launch and reentry, and robotics. Its developments include a joint venture for a lunar payload delivery service, and a robotic arm, the Walking Manipulator.
Country: Belgium
Type: Industry
Year Founded: 1987
URL: https://www.spaceapplications.com/
State of Play Entries: PRUMI05

8.69 Spaceflight

Description: Spaceflight was an aerospace company that provided rideshare launch opportunities, in-space transportation, and other mission services. Its developments included an array of on-orbit Sherpa vehicles that provided transportation and avionics to hosted payloads. Spaceflight was acquired by Firefly Aerospace in 2023.
Country: United States
Type: Industry
Year Founded: 2011
URL: https://spaceflight.com/
State of Play Entries: R14

8.70 SpaceWorks Enterprises Inc

Description: SpaceWorks is an aerospace company that provides engineering services to government and industry customers in the areas of design, prototyping, and flight demonstrations.
Country: United States
Type: Industry
Year Founded: 2000

URL: https://www.spaceworks.aero/
State of Play Entries: PRUMI03

8.71 SpaceX

Description: SpaceX is an aerospace company that develops and operates launch vehicles and communications satellites. SpaceX pioneered reusability and quick turnover launch availability with their Falcon 9 and Falcon Heavy launch systems, and they are currently operating the Starlink communications constellation. Its current developments include the Starship super heavy-lift space vehicle, which will also include on-orbit cryogenic propellant transfer.
Country: United States
Type: Industry
Year Founded: 2002
URL: https://www.spacex.com/
State of Play Entries: RFT09

8.72 Spar Aerospace

Description: Spar Aerospace was an aerospace company which provided technology solutions to the Canadian Space Agency in support of the American Shuttle Program. Spar was responsible for providing the Canadarm for the Space Shuttle and the Canadarm2 for the ISS. Spar Aerospace is now part of MDA Space.
Country: Canada
Type: Industry
Year Founded: 1967
URL: N/A
State of Play Entries: RM02

8.73 Starfish Space

Description: Starfish Space is an aerospace company specializing in satellite servicing. The company develops satellite servicing technologies such as rendezvous and capture software and robotics, and it plans to offer satellite mission extension, debris removal, and autonomous transportation.
Country: United States
Type: Industry
Year Founded: 2019
URL: https://www.starfishspace.com/
State of Play Entries: RCDM19, RCDM22, RCDM23, R10

8.74 Tethers Unlimited Inc

Description: Tethers Unlimited Inc is an aerospace company specializing in space debris mitigation, in-space transportation, and other areas of space logistics. The company is part of the ARKA group, and its developments include robotic assembly and fabrication technologies, small satellite subsystems, and

satellite communications technologies.
Country: United States
Type: Industry
Year Founded: 1994
URL: https://www.tethers.com/
State of Play Entries: RM13, RCDM14, PRUMI01, ULRM01, SMA11, RRR01, RRR02, RRR03, PGM07

8.75 The Aerospace Corporation

Description: The Aerospace Corporation is a Federally Funded Research and Development Center (FFRDC) in El Segundo, California. It provides aerospace consulting and technical guidance to the national security and civil space sectors.
Country: United States
Type: Industry
Year Founded: 1960
URL: https://aerospace.org/
State of Play Entries: RCDM02, IM01

8.76 The Boeing Company

Description: The Boeing Company is a global aerospace company specializing in the development, manufacture, and servicing of commercial airplanes, defense, and space systems. It has developed numerous spacecraft, including much of the International Space Station structural assembly.
Country: United States
Type: Industry
Year Founded: 1916
URL: https://www.boeing.com/
State of Play Entries: RCDM24, SMA12, SMA17, SMA23

8.77 The University of Texas at Austin (UT Austin)

Description: The University of Texas at Austin is a public research university in Austin, Texas. The Austin campus is the flagship campus of the University of Texas university system, and it employs 3,000 teaching faculty and is home to over 52,000 students.
Country: United States
Type: Academia
Year Founded: 1883
URL: https://www.utexas.edu/
State of Play Entries: IM15

8.78 TsKBEM
Description: TsKBEM, which translates to the Central Design Bureau of Experimental Machine Building, was a previous name of RKK Energiya. This company is a Russian manufacturer of spacecraft and space components. It developed the SSVP docking system, a system to enable the rendezvous and capture, docking, and crew transfer used on most Soviet and Russian crewed space vehicles
Country: USSR
Type: Industry
Year Founded: 1946
URL: N/A
State of Play Entries: RCDM34

8.79 Union of Soviet Socialist Republics (USSR)
Description: The Union of Soviet Socialist Republics was a country founded in 1922 and dissolved in 1991. The country played a critical role in the "Space Race" of the 20th century, launching the first artificial Earth satellite in 1957 and the first human in space 1961, and acting as the main rival of the United States in the race to put a human on the Moon.
Country: USSR
Type: Government
Year Founded: 1922
URL: N/A
State of Play Entries: SMA18, SMA27

8.80 United Kingdom Space Agency (UKSA)
Description: The United Kingdom Space Agency is the executive agency of the United Kingdom charged with the development and implementation of its space program. Its current developments include a joint venture with Astroscale to decommission two defunct British satellites currently orbiting Earth by 2026.
Country: United Kingdom
Type: Government
Year Founded: 2010
URL: https://www.gov.uk/government/organisations/uk-space-agency
State of Play Entries: RCDM08

8.81 United Launch Alliance (ULA)
Description: United Launch Alliance (ULA) is an aerospace, defense, and launch service provider formed by a joint venture between Lockheed Martin and The Boeing Company. ULA manufactures and operates launch vehicles such as their Atlas V and Delta IV Heavy rockets, and it is currently developing the Vulcan Centaur heavy-lift launch vehicle.
Country: United States
Type: Industry

Year Founded: 2006
URL: https://www.ulalaunch.com/
State of Play Entries: RFT09

8.82 United States Army Corps of Engineers

Description: The U.S. Army Corps of Engineers is a group within the United States Army which offers engineering services through a civilian and military workforce. The Corps' 37,000 employees offer engineering solutions in areas such as infrastructure maintenance and military facility installation both domestically and abroad.
Country: United States
Type: Government
Year Founded: 1802
URL: https://www.usace.army.mil/
State of Play Entries: SC02

8.83 United States Department of Energy (DOE)

Description: The U.S. Department of Energy is a department of the executive branch of the United States which is responsible for managing the U.S. nuclear infrastructure, administering U.S. energy policy, and funding research and development of energy technologies. The department operates 17 research and development facilities across the United States.
Country: United States
Type: Government
Year Founded: 1977
URL: https://www.energy.gov/
State of Play Entries: IM02

8.84 University of Arizona

Description: The University of Arizona is a public research university in Tucson, Arizona. The university employs 3,300 faculty and is home to more than 51,000 students.
Country: United States
Type: Academia
Year Founded: 1885
URL: https://www.arizona.edu/
State of Play Entries: RM18

8.85 University of Delaware

Description: The University of Delaware is a state-assisted, privately governed, teir-1 research university in Newark, Delaware. The university employs over 1300 faculty, is home to more than 23,000 students, and operates 80 university research centers.
Country: United States

Type: Academia
Year Founded: 1743
URL: https://www.udel.edu/
State of Play Entries: RRR04

8.86 University of Maryland Space Systems Laboratory (UMD SSL)

Description: The University of Maryland Space Systems Laboratory (UMD SSL) is a research facility located at the University of Maryland College Park campus. The SSL is centered around the lab's Neutral Buoyancy Research Facility, a 50-foot diameter, 25-foot deep, 367,000-gallon water tank used to conduct research in a simulated in-space environment.
Country: United States
Type: Academia
Year Founded: 1976
URL: https://ssl.umd.edu/
State of Play Entries: RM24

8.87 Visioneering Space Corporation

Description: Visioneering Space Corporation is a space engineering company focused on designing and building spaceflight and scientific research systems. Its developments in mechanical, electro-mechanical, and opto-mechanical engineering include the Mars Atmosphere and Volatile EvolutionN satellite (MAVEN), the Neutron star Interior Composition ExploreR (NICER), the Sample Analysis at Mars instrument on the Curiosity Rover, and the Lunar Atmosphere and Dust Environment Explorer (LADEE).
Country: United States
Type: Industry
Year Founded: 2000
URL: https://www.visioneeringspace.com/
State of Play Entries: PGM05

8.88 Westinghouse Electric Company

Description: Westinghouse Electric Company is an energy technology company formed in 1999 as a spinoff from the Westinghouse Electric Corporation. Westinghouse Electric Company focuses on the supply of nuclear energy technology and services.
Country: United States
Type: Industry
Year Founded: 1886
URL: https://www.westinghousenuclear.com/
State of Play Entries: SMA20

9 Appendix – ISAM Facilities

9.1 Additive Manufacturing Facility (AMF)

Description: The ISS Additive Manufacturing Facility (AMF) is an innovative 3D printing facility aboard the International Space Station (ISS), jointly developed by NASA and Made In Space, Inc. This facility empowers astronauts to fabricate tools, parts, and customized items directly on the ISS, reducing the need for resupply missions from Earth and enabling in-situ resource utilization.
Type: NASA
Location: ISS
URL: https://ntrs.nasa.gov/api/citations/20160011465/downloads/20160011465.pdf
Related Capability Area(s): PGM

9.2 Astrobee Microgravity Test Facility

Description: Astrobee is NASA's new free-flying robotic system replacing the SPHERES robots on the ISS.
Type: NASA
Location: ISS
URL: https://www.nasa.gov/astrobee
Related Capability Area(s): RM, IM

9.3 Autonomy Lab for Intelligent Flight Systems (A-LIFT)

Description: The NASA LaRC Autonomy Lab for Intelligent Flight Systems aims to prepare its workforce for upcoming autonomy and robotics challenges in space exploration and aeronautics, supporting complex missions like asteroid retrieval, planetary exploration, pollution measurements, and UAS integration. The lab includes an outdoor flying space of 60 by 60 feet and 50 feet tall, along with an indoor flight space measuring 1680 square feet.
Type: NASA
Location: LaRC
URL: https://researchdirectorate.larc.nasa.gov/a-lift/
Related Capability Area(s): IM

9.4 Berkeley Robotics and Intelligent Machines /High Performance Robotics (HiPeR) Lab

Description: low-level research on fundamental robotics capabilities, especially for Unmanned Aerial Systems. Areas of particular focus are safety, localization, and design. We aim to enhance the systems' capabilities by advanced algorithms, mechanical design, and control strategies.
Type: Academia
Location: University of California-Berkeley, Berkeley, CA
URL: https://me.berkeley.edu/research-areas-and-major-fields/laboratories/
Related Capability Area(s): IM

9.5 Coded Structures Laboratory

Description: The Coded Structures Lab (CSL) is applying programmable material, mechanical-meta material, and autonomy principles to develop In-Space Assembly Robotic Construction Systems. The lab is equipped with rapid prototyping equipment, mechanical testing equipment, and facilities to test robotic assembly.
Type: NASA
Location: ARC
URL: https://www.nasa.gov/ames/ocs/seminars/kenneth-cheung
Related Capability Area(s): SMA

9.6 Collaborative and Autonomous Vehicle Ecosystem (CAVE)

Description: The Collaborative and Autonomous Vehicle Ecosystem (CAVE) is located in the Guidance and Control Systems Labs at the Aerospace Corporation, and it provides an environment for research, development, integration, and testing of autonomous subsystems and systems with robotic arms, rovers, and drones. The lab's goal is to explore how increased autonomy and collaborative robotics enable autonomous space systems.
Type: Aerospace Corporation
Location: Los Angeles, CA
URL: https://aerospace.org/sites/default/files/GCS/
Related Capability Area(s): RCDM, SC, PRUMI, RM

9.7 Collaborative Robotics and Intelligent Systems Institute (CoRIS)

Description: studying technological advancement, while considering how the robots impact people and how the changes brought by the widespread use of robots will shape our society.
Type: Academia
Location: Oregon State University, Corvallis, OR
URL: https://engineering.oregonstate.edu/CoRIS
Related Capability Area(s): IM

9.8 Dynamic and Autonomous Robotic Systems (DARoS) Lab

Description: The DARoS Laboratory is creating robotic systems for common goods. The primary research area is in the dynamic locomotion of legged systems with a focus on the development of control architectures and their experimental validation. The ultimate goal of the group is to develop robots to be practical tools for human life by enhancing robotic systems to be faster, smarter, and more robust.
Type: Academia
Location: University of Massachusetts-Amherst, Amherst, MA
URL: https://www.umass.edu/robotics/daros
Related Capability Area(s): RM

9.9 Edwards Air Force Base

Description: Edwards Air Force Base is a U.S. Air Force installation focused on conducting tests and demonstrations of aircraft and spacecraft for the U.S. military. AFRL's Propulsion Directorate maintains the AFRL Rocket Lab, which contributes to research on in-space propulsion, green propellants, modular propulsion units, and the cislunar logistics chain.
Type: AFRL
Location: Edwards Air Force Base, CA
URL: https://www.edwards.af.mil/
Related Capability Area(s): RPOC, RFT, ULRM, PRUMI

9.10 Express Logistics Carrier

Description: The Express Logistics Carriers (ELC) is designed to provide additional storage and support for external payloads aboard the ISS. Developed by NASA, the ELC is an external platform attached to the ISS's truss structure, facilitating the mounting of various scientific instruments, spare parts, and equipment.
Type: NASA
Location: ISS
URL: https://www.nasa.gov/mission_pages/station/structure/elements/express-logistics-carriers/
Related Capability Area(s): PRUMI

9.11 Flight Robotics Laboratory

Description: Marshall's testing facility consists of the Flight Robotics Laboratory (FRL) with a large precision air-bearing floor, offering 8 degrees of freedom for simulating relative motion, and a dynamic lighting simulator for sun motion and brightness simulation. This enables the FRL to test various objects, including full systems, spacecraft, sensors, and cameras, with recent testing of Proximity Operations Sensors for the Dragon capsule in support of SpaceX.
Type: NASA
Location: MSFC
URL: https://www.nasa.gov/sites/default/files/atoms/files/msfc_capabilities_06_16_mobile.pdf
Related Capability Area(s): RM, SC, IM

9.12 Flight Simulation Facilities (FSF)

Description: The Flight Simulation Facilities include various simulation setups such as the Cockpit Motion Facility, Research Flight Deck, Development and Test Simulator, and more. These simulators offer high-fidelity, real-time, human-in-the-loop flight capabilities for conducting aerospace research.
Type: NASA
Location: LaRC
URL: https://csaob.larc.nasa.gov/facilities/?doing_wp_cron=1689264976.5941989421844482421875
Related Capability Area(s): IM

9.13 Fluid Transfer Lab in the Vehicle Assembly Building

Description: The KSC EDO has been used in collaboration with GSFC to develop fluid transfer components and subsystems. It was used as a test area to advance the design for the OSAM-1 Propellant Transfer System (PTS). It has also been used to advance other R&T efforts related to on-orbit fluid transfer. With the 50'x50' floor footprint, it is ideal for large test setups that require an indoor facility. In addition, a large quantity of fluids test equipment is readily available to support a broad array of testing.
Type: NASA
Location: KSC
Related Capability Area(s): RFT, IM

9.14 Formation Control Testbed

Description: The Formation Control Testbed (FCT) is used for developing autonomous guidance, navigation and control (GNC) algorithms and relative sensor technologies. Its unique capabilities allow high fidelity, system-level ground testing of spacecraft architectures and autonomous operations.
Type: NASA
Location: JPL
URL: https://scienceandtechnology.jpl.nasa.gov/formation-control-testbed-fct
Related Capability Area(s): RCDM

9.15 General Robotics, Automation, Sensing and Perception (GRASP) Laboratory

Description: Founded in 1979, the GRASP Lab is a premier robotics incubator that fosters collaboration between students, research staff and faculty focusing on fundamental research in vision, perception, control systems, automation, and machine learning.
Type: Academia
Location: University of Pennsylvania, Philadelphia, PA
URL: https://www.grasp.upenn.edu/
Related Capability Area(s): IM

9.16 Hexapod Robot: Autonomous Rendezvous & Grasp for Planned and Unplanned Clients

Description: This new and unique robot is designed to test robotic satellite servicing capabilities. Standing 10 feet tall and 16 feet wide, the six-legged “hexapod” robot helps engineers perfect technologies before they’re put to use in space.
Type: NASA
Location: GSFC
URL: https://ntrs.nasa.gov/citations/20160010251
Related Capability Area(s): IM

9.17 Human-Center Robotics Lab; Robot Learning Lab; Robotics and State Estimation Lab

Description: Robotics researchers are engaged in ground-breaking work in mechanism design, sensors, computer vision, robot learning, Bayesian state estimation, control theory, numerical optimization, biomechanics, neural control of movement, computational neuroscience, brain-machine interfaces, natural language instruction, physics-based animation, mobile manipulation, and human-robot interaction.
Type: Academia
Location: University of Washington-Seattle, Seattle, WA
URL: https://robotics.cs.washington.edu/
Related Capability Area(s): IM, RM

9.18 Integrated Structural Assembly of Advanced Composites (ISAAC)

Description: ISAAC is a highly accurate, automated robotic platform used to support research on the design, analysis, manufacturing and evaluation of advanced composite materials and structures.
Type: NASA
Location: LaRC
URL: https://researchdirectorate.larc.nasa.gov/isaac/
Related Capability Area(s): RM, SC

9.19 ISAM Test Laboratory

Description: Supports full-scale autonomous assembly of large space structures. Multi-level facility (recessed floors and elevated ceilings) that will enable operational testing of environmental scenarios (orbital, surface, and sub-surface). Integration of LaRC's expertise and capabilities in autonomy, structures, predictive modeling, simulation, and systems analysis. Attached to the lab is a room with dark walls and ceiling to support testing of sub-scale autonomous robotic operations and testing metrology systems.
Type: NASA
Location: LaRC
Related Capability Area(s): RM

9.20 JEM External Facility

Description: The Japanese Experiment Module's Exposed Facility (JEM EF) is an external platform on the International Space Station (ISS), developed by the Japan Aerospace Exploration Agency (JAXA). It enables the installation of scientific experiments and instruments exposed directly to the space environment, fostering a wide range of research activities in microgravity conditions.
Type: JAXA
Location: ISS
URL: https://humans-in-space.jaxa.jp/en/biz-lab/experiment/facility/ef/
Related Capability Area(s): RM

9.21 Kirtland Air Force Base

Description: Kirtland Air Force Base specializes in research, development, and testing among its other missions and is home to AFRL's Space Vehicles Directorate which develops and transitions new space technologies to national security space use. The Space Warfighting Operations Research and Development (SWORD) Laboratory is a 26,000 square foot facility that hosts research and development programs that support space warfighting capabilities, including space domain awareness, spacecraft resilience, and autonomy.
Type: AFRL
Location: Kirtland Air Force Base, NM
URL: https://www.afrl.af.mil/News/Article-Display/Article/2629320/afrl-opens-space-warfighting-operations-research-and-development-sword-laborato/
Related Capability Area(s): RCDM, PRUMI, IM, ULRM, R

9.22 Laboratory for Computational Sensing and Robotics (LCSR)

Description: LCSR's mission is to create knowledge and foster innovation to further the field of robotics science and engineering.
Type: Academia
Location: Johns Hopkins University, Baltimore, MD
URL: https://lcsr.jhu.edu/
Related Capability Area(s): IM

9.23 Lunar Lab and Regolith Testbeds

Description: The Lunar Lab and Regolith Testbeds are facilities equipped with different types of lunar simulant and can be customized to test specific research investigations. Currently, it is being used to test the VIPER optical system.
Type: NASA
Location: ARC
URL: https://sservi.nasa.gov/testbed/
Related Capability Area(s): SC

9.24 Maryland Robotics Center

Description: This interdisciplinary research facility studies all aspects of robotics including intelligence, component technologies, and system autonomy.
Type: Academia
Location: University of Maryland, College Park, MD
URL: https://robotics.umd.edu/facilities
Related Capability Area(s): RM

9.25 Materials and Processes Laboratory

Description: The laboratory provides capabilities including: Materials Testing, Nonmetallic Materials and Manufacturing, Materials Selection and Control & Informatics, Damage Tolerance Assessment, Environmental Effects, and Metallic Engineering In-Space Manufacturing Material and Processing Development Mechanical Test and Characterization Space Environmental Effects (SEE) Test Lab
Type: NASA
Location: MSFC
URL: https://www.nasa.gov/sites/default/files/atoms/files/5-565173b_mpl.pdf
Related Capability Area(s): PGM

9.26 Measurement System Laboratory (MSL)

Description: The MSL is a 175,000-square-foot, five-story laboratory containing 40 state-of-the-art research labs and workspace to enable the development, testing, and implementation of new sensor and instrument technologies. Serving as the primary research and development facility for multiple NASA focus areas, the goal of the MSL is to enable the agency in achieving its missions in space exploration, science, and aeronautics with a flexible, modular design that utilizes shared facilities and capability with an emphasis on collaboration.
Type: NASA
Location: LaRC
URL: https://www.youtube.com/watch?v=-Yn5k7_fQys
Related Capability Area(s): IM

9.27 Naval Center for Space Technology (NCST)

Description: The Naval Center for Space Technology (NCST) at the U.S. Naval Research Laboratory (NRL) assists with the development of all areas of Navy space program interest from basic research to spacecraft development. The Robotic Servicing of Geosynchronous Satellites (RSGS) robotic servicing payload is being developed and tested at NCST.
Type: NRL
Location: Washington, DC
URL: https://www.nrl.navy.mil/Our-Work/Areas-of-Research/Naval-Center-for-Space-Technology/
Related Capability Area(s): PRUMI, RM, RCDM

9.28 Planetary Analog Test Site

Description: Planetary Analog Test Site, known as the Rock Yard, at NASA's Johnson Space Center in Houston, provides a large multi-acre test area which simulates general features of the lunar and Martian surface terrain environment consisting of various slopes, grades, simulated craters and strewn rock field conditions.
Type: NASA
Location: JSC
URL:

https://www.nasa.gov/centers/johnson/engineering/integrated_environments/space_analog_testing/index.html
Related Capability Area(s): RM, SC, IM

9.29 Raven

Description: Raven is a NASA flight experiment conducted on the International Space Station (ISS) to facilitate the development and validation of Autonomous Rendezvous and Capture (AR&C) technologies. Its mission aims to demonstrate advanced sensors, vision processing algorithms, and high-speed space-rated avionics, forming an autonomous navigation system.
Type: NASA
Location: ISS
URL: https://nexis.gsfc.nasa.gov/raven.html
Related Capability Area(s): RPOC

9.30 ReFabricator

Description: ReFabricator is an advanced recycling system aboard the International Space Station (ISS), developed by NASA in collaboration with Tethers Unlimited Inc. It facilitates the recycling of plastic waste and 3D printing of new items, promoting sustainability and reducing the reliance on resupply missions from Earth.
Type: NASA
Location: ISS
URL: https://science.nasa.gov/science-news/news-articles/the-in-space-refabricator
Related Capability Area(s): PGM

9.31 Robotic Operations Center

Description: The Robotic Operations Center, or ROC, is the newest facility for satellite servicing development. Within its black, curtain-lined walls, the team is testing technologies and operations for multiple exploration and science missions, including the OSAM-1 mission. The ROC has been continuing and expanding the work of the Servicing Technology Center since the summer of 2015 and houses multiple robots including a hexapod robot which simulates the movement of a satellite in space.
Type: NASA
Location: GSFC
URL: https://nexis.gsfc.nasa.gov/facility.html
Related Capability Area(s): RM

9.32 Robotics and Autonomous Systems Center (RASC)

Description: RASC research spans the major areas of robotics, including health, service, socially assistive, distributed, networked, marine, aerial, humanoid, haptics, space, robot vision and robot learning, and impacts a broad spectrum of applications, including assistance, training and rehabilitation, education, environmental monitoring, emergency response, homeland security, and entertainment.

Type: Academia
Location: University of Southern California, Los Angeles, CA
URL: https://rasc.usc.edu/
Related Capability Area(s): IM

9.33 Robotics and Mechanisms Lab (RoMeLa)

Description: RoMeLa is a state-of-the-art robotics research facility for graduate and undergraduate research and education with an emphasis on studying robotics.
Type: Academia
Location: University of California, Los Angeles, CA
URL: https://www.romela.org/
Related Capability Area(s): RM

9.34 Robotics and Mechtronics Lab

Description: Students can study areas such as robotic intelligence, vision, system dynamics and control, human-robotic interactions, machine learning, industrial automation.
Type: Academia
Location: Virginia Polytechnic Institute and State University, Blacksburg, VA
URL: https://autonomyandrobotics.centers.vt.edu/groups/rml.html
Related Capability Area(s): IM, RM

9.35 Robotics Lab

Description: The Planetary Robotics Laboratory (PRL) is a facility dedicated to rapid prototyping of robotic systems and algorithms for space and terrestrial applications. It focuses on designing, testing, and coordinating mobile and manipulative robots, including limb-controlled robots for in-space construction and multiple heterogeneous rovers for surface operations, with simulated natural terrain capabilities.
Type: NASA
Location: JPL
URL: https://www-robotics.jpl.nasa.gov/
Related Capability Area(s): RM

9.36 Roverscape

Description: The NASA Ames Roverscape is an 11,500 square meter, outdoor, robotics research, development, and test facility. The Roverscape is designed to support testing of mobile robot locomotion, navigation, and operations. The Roverscape is also suitable for conducting simulations of planetary surface missions.
Type: NASA
Location: ARC

URL: https://www.nasa.gov/feature/roverscape
Related Capability Area(s): SC

9.37 Satellite Servicing Technology Center

Description: The Servicing Technology Center (STC), established in 2011, serves as a pivotal hub for technology and operations development. With a primary focus on NASA's Robotic Refueling Mission (RRM), the STC facilitates the integration, testing, and refinement of satellite-servicing tools and techniques for on-orbit operations on the International Space Station, contributing significantly to the advancement of space robotics.
Type: NASA
Location: GSFC
URL: https://nexis.gsfc.nasa.gov/facility.html
Related Capability Area(s): PRUMI

9.38 Simulated Lunar Operations Laboratory

Description: The SLOPE lab is a unique indoor laboratory designed to mimic lunar and planetary surface operations. The lab contains several large soil bins for rover testing, including an adjustable tilt-bed as well as equipment for evaluating performance of tires, excavation tools and other vehicle components.
Type: NASA
Location: GRC
URL: https://www.nasa.gov/nasaglenntours/2023/the-simulated-lunar-operations-lab-slope-tour/
Related Capability Area(s): SC

9.39 Small Satellite Dynamics Testbed

Description: The Small Satellite Dynamics Testbed (SSDT) at the Jet Propulsion Laboratory offers infrastructure that supports small satellite guidance and control testing in a relevant dynamics environment while constrained by the gravity of Earth.
Type: NASA
Location: JPL
URL: https://scienceandtechnology.jpl.nasa.gov/small-satellite-dynamics-testbed-ssdt
Related Capability Area(s): RCDM

9.40 Space Rendezvous Laboratory (SLAB)

Description: (SLAB) is a research and development laboratory that performs fundamental and applied research at the intersection of Astrodynamics, GN&C, Environment Characterization and Decision Making to enable future Distributed Space Systems (DSS).
Type: Academia
Location: Stanford
URL: https://slab.stanford.edu/
Related Capability Area(s): IM

9.41 Space Robotics Laboratory (SRL)

Description: The Space Robotics Laboratory at the U.S. Naval Research Laboratory (NRL) provides testbeds to develop robotic systems and demonstrate their operations. The lab enables hardware-in-the-loop testing and is supporting the test and development of the Robotic Servicing of Geosynchronous Satellites (RSGS) robotic servicing payload.
Type: NRL
Location: Washington, DC
URL: https://www.nrl.navy.mil/Our-Work/Areas-of-Research/Naval-Center-for-Space-Technology/
Related Capability Area(s): PRUMI, RM, RCDM

9.42 Space Systems Laboratory and the Neutral Buoyancy Research Facility

Description: The Space Systems Laboratory is centered around the Neutral Buoyancy Research Facility, a 50-foot diameter, 25-foot deep water tank that is used to simulate the microgravity environment of space. These facilities specialize in astronautics and the simulation of microgravity environments.
Type: Academia
Location: University of Maryland, College Park, MD
URL: https://ssl.umd.edu/about
Related Capability Area(s): IM

9.43 Spacecraft Structures and Dynamics Lab

Description: The research complex, established in 1962, supports spacecraft and launch vehicle dynamics research, featuring a 55-foot Vacuum Chamber and a previously used 60-foot Vacuum Sphere. The facility includes a large backstop for structural dynamics testing of launch vehicles and spacecraft components, along with a 107-foot tower used for model tests of the US Air Force Thor family of launch vehicles, now primarily dedicated to deployable space structures research.
Type: NASA
Location: LaRC
URL: https://researchdirectorate.larc.nasa.gov/facilities-capabilities/
Related Capability Area(s): RM, IM, SC

9.44 Structures and Materials Lab

Description: The James H Starnes, Jr. Structures and Materials Lab conducts materials and structural analysis for aircraft design and development of new structural concepts for aeronautical and space vehicles. The facility focuses on experiments in metallurgy, composite materials, environmental effects, and manufacturing technology to create materials that can withstand various conditions. Additionally, the lab houses NINJAR and SAMURAI robots and features a 1.2 million pound force test frame from the 1940s, used for researching robotics and in-space assembly.
Type: NASA
Location: LaRC

URL: https://ntrs.nasa.gov/citations/20220014087
Related Capability Area(s): SC, RM, SMA

9.45 Swamp Works Laboratory

Description: Research and Technology Incubator based out of Kennedy Space Center's Science and Technology Division. This lab hosts a range of projects including: applied physics; applied chemistry; granular mechanics and regolith operations; cryogenics; electrostatics and surface physics; regolith activities testing; robotics integration, checkout and assembly; corrosion technology; advanced materials and polymer science, advanced manufacturing and 3-D printing.
Type: NASA
Location: KSC
URL: https://www.nasa.gov/sites/default/files/atoms/files/sp-2017-01-008-ksc_ub_swamp_works_flyer_508.pdf
Related Capability Area(s): RM, PGM, SC, IM

9.46 The Institute for Robotics and Intelligent Machines

Description: Fundamental research includes expertise in mechanics, control, perception, artificial intelligence and cognition, interaction, and systems.
Type: Academia
Location: Georgia Institute of Technology, Atlanta, GA
URL: https://research.gatech.edu/robotics
Related Capability Area(s): RM

9.47 The Robotics Institute

Description: Established in 1979 to conduct basic and applied research in robotics technologies
Type: Academia
Location: Carnegie Mellon University, Pittsburg, PA
URL: https://www.ri.cmu.edu/about/
Related Capability Area(s): RM

9.48 The University of Michigan Robotics Institute

Description: The University designed the space to serve as collaborative labs and classrooms, with an indoor flight lab for flying autonomous vehicles, an outdoor playground for testing robots, and a partnership with Ford Motor Company, whose employees will share the building with students and faculty.
Type: Academia
Location: University of Michigan, Ann Arbor, MI
URL: https://robotics.umich.edu/
Related Capability Area(s): RM

9.49 Water Hammer and Fluids Lab

Description: The GSFC Fluids Lab has been used in collaboration with KSC to develop fluid transfer components and subsystems. It was used as a manufacturing and assembly area to fabricate the OSAM-1 Propellant Transfer System (PTS). It has also been used to advance other R&D efforts related to on-orbit fluid transfer.
Type: NASA
Location: GSFC
Related Capability Area(s): RFT

9.50 Wright-Patterson Air Force Base

Description: Wright-Patterson Air Force Base is one of the largest Air Force bases in the United States and, among other functions, houses the headquarters for the Air Force Research Laboratory (AFRL). AFRL facilities support robotic control systems, additive manufacturing for space systems, advanced materials for in-space manufacturing and assembly.
Type: AFRL
Location: Wright-Patterson Air Force Base, OH
URL: https://www.afrl.af.mil/
Related Capability Area(s): SMA, PGM

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