RELEASE DATE: 7/7/2026

COSMIC-E01-C004-2026-A

COSMIC

CONSORTIUM FOR SPACE MOBILITY AND ISAM CAPABILITIES

A CROSS-DISCIPLINARY STUDY OF IN-SPACE UPGRADE, REPAIR, AND REPLACEMENT OF SPACECRAFT COMPONENTS

Aimee Hubble, COSMIC Consortium Management Entity, Sr. Project Engineer, The Aerospace Corporation
Alec Cavaciuti, COSMIC Consortium Management Entity, Sr. Member of the Technical Staff, The Aerospace Corporation

REVISION AND HISTORY PAGE

Revision No.	Description	Release Date
Baseline	Initial Baseline	TBD

Contents

Acknowledgements

This report represents contributions from the entire COSMIC consortium, with particular contributions from the following individuals:

Anthony Brich, Rogue Space

Ben Rupp, NASA Marshall Space Flight Center (MSFC)

Bernard Kelm, United States Naval Research Laboratory (NRL)

Bo Naasz, NASA Goddard Space Flight Center (GSFC)

Dallas Bienhoff, Offworld Inc.

Dave Barnhart, Arkisys

Greg Vialle, Lunexus Space

John Mulvaney, NASA Langley Research Center (LaRC)

JT Honning, Amptec Research

Mark Neuman, Stellar Solutions, Inc.

Mathis Shinnick, Hanserd Holdings

Matt Klicka, Quartus Engineering

Noah Gladden, Arkisys

Richard Nederlander, Spargo Space

Stephen Leete, SpaceLogistics

Tom McCarthy, Motiv Space Systems

1. Introduction

1.1 COSMIC Use Case Reports

The Consortium for Space Mobility and ISAM Capabilities (COSMIC) is a U.S. consortium comprised of member organizations spanning industry, academia, and government. COSMIC's primary goal is to accelerate the universal adoption of in-space servicing, assembly, and manufacturing (ISAM) capabilities for the next generation of space architectures and make ISAM a routine part of the space enterprise. This report provides a thorough interrogation of a specific ISAM use case—in-space upgrade, repair, and replacement of spacecraft components—to detail the use case's concept of operations (CONOPS), assess gaps in available reliant technology, highlight shortfalls in current demonstration infrastructure, and discuss policy and regulatory challenges relevant to the use case.

As defined by the COSMIC ISAM Lexicon, an ISAM use case is a baseline or alternative scenario where ISAM capabilities are employed to enhance or enable a mission opportunity [1]. In 2024, COSMIC defined 30 such ISAM use cases which were reviewed and prioritized by COSMIC's advisory Steering Committee. The first use case report, released in 2025, focused on geostationary orbit (GEO) refueling [2]. This document is the second use case report produced by COSMIC and provides a comprehensive ISAM community perspective.

Technical inputs to this use case report were gathered from the consortium's more than 1200 members , reflecting knowledge and perspectives from satellite-servicing providers, government and commercial customers, researchers, regulators, and other organizations with a vested interest in ISAM.

1.1.1 Upgrade, Repair, and Replacement of Spacecraft Components

The core definition of this use case is to employ ISAM capabilities to physically alter a space vehicle after its launch. The three major subcategories that have been defined are:

Table 1. Upgrade, Repair, and Replacement Definitions

Operation	Definition	Examples
Upgrade	Improvement of a spacecraft's capabilities or the introduction of new capabilities through servicing. Note: This can be done by either replacing an existing component with one with upgrade features, or attaching a new component externally with upgrade features, referred to as augmentation.	Remove a planned Orbital Replacement Unit (ORU) and install a compatible ORU with upgraded capability. Augmentation involves upgrading capabilities by attaching a stand-alone package, such as a propulsion unit or add-on Space Domain Awareness (SDA) capability.

Repair	The re-establishment of spacecraft capabilities as originally designed through servicing.	Break friction on a jammed boom deployment or clear a loose thermal blanket affecting mechanism function.
Replace	The physical swap of components or installation of units with identical functionality through servicing.	Replace a pre-planned ORU (e.g., an electronics box, reaction wheel, etc.) with an identical unit.

All three of these operations are accomplished through satellite servicing involving both servicer and client spacecraft, though each provides a different value proposition. Upgrade is typically seen as the most valuable since it expands mission capability, and it can be performed either by exchanging an old or broken component with an improved one or by attaching new state-of-the-art equipment to the existing spacecraft. Repair, on the other hand, has the highest utility towards the beginning of the mission. Moreover, for a typical mission lasting 10 or more years, a failed component or subsystem is likely out of date compared to the current state of the art. For the effort required to plan and execute a servicing mission, it is unlikely that a component would be replaced with the same technology that was available at launch, but rather with a modern and more capable component with the same interfaces.

In an example scenario of replacing a degraded processor on a satellite with one that is more powerful than the original, our definitions of upgrade, repair, and replacement overlap. While the operation could simultaneously be considered an upgrade, a repair, and a replacement, for the purposes of this report, this operation is categorized as an upgrade that is provided by a servicer which performs a replacement operation. In this example, the core capabilities of a spacecraft are not only repaired, but upgraded and better reflect a modern system. The CONOPS of upgrade, repair, and replacement can look very similar in terms of operations, even if the triggering event driving the service differs. A repair fixes something that is broken and can be achieved via component replacement or through refurbishment of the broken part, whereas an upgrade can be achieved via a replacement of a component that is outdated, degraded, or insufficient for current mission needs. A repair can also be achieved without a replacement operation, for example, by using a robotic manipulator to unjam a stuck solar panel deployment.

A higher level of "preparedness" or "serviceability" of a client directly lowers the complexity of the servicing operation, thereby lowering the costs and allowing for more servicing business cases to close. Given the lack of serviceable spacecraft currently in orbit and the current low but growing demand for upgrade services, a more likely scenario to achieve a repair or upgrade is through the addition of new equipment or components attached externally to the existing spacecraft, a process frequently referred to as augmentation.

Augmentation in this context is a method of accomplishing an upgrade or functional replacement. From an engineering perspective, augmentation is much simpler to implement both in an unprepared and prepared capacity than operations requiring manipulation of a space vehicle's interior—colloquially referred to as "satellite surgery." While *unprepared* augmentation can be achieved through attaching external boxes to monolithic or legacy satellites, *prepared* augmentation has the potential to achieve broader space enterprise effects by leveraging a future ecosystem of upgradable and serviceable spacecraft.

Enabling serviceability through prepared augmentation requires some sort of access port or interface designed into a satellite from the beginning. This could be as simple as utilizing an existing ground test port or a dedicated in-space connectible interface, either of which would allow an externally mounted box to access power, data, and communication assets within the rest of the spacecraft bus. Standardization is key to enhancing the value proposition of this use case, enabling a single servicing architecture to provide upgrade capability to as many satellites fitted with a compatible upgrade interface as possible. A data interface architecture like "USB for space" could allow space vehicles to be designed with future upgrades in mind, with the installation of new or improved capabilities just like peripherals are installed on computer systems on the ground. Standardizing this interface eliminates mission unique engineering cost that would otherwise be associated with designing for augmentation capability and allows for broadest flexibility of a servicing vehicle to address the specific needs of as many clients as possible. Interface standardization could also enable an orbital depot architecture in which Orbital Replacement Units (ORUs) are stored on orbit for future distribution.

1.2 Historical Perspective and Current Missions

With the notable exception of Northrop Grumman's Mission Robotic Vehicle (MRV), there is currently a lack of servicing spacecraft capable of providing upgrade, repair, and replacement services. Satellite developers are not yet designing for servicing beyond basic fiducials, and servicers will not be built at scale until satellite developers build in serviceability. There is a cost associated with both sides of that problem: designing for serviceability involves a more modest but very widespread cost across the entire space enterprise. Producing the infrastructure such as servicing vehicles and depots needed for a servicing ecosystem represents a large cost that needs to be amortized across many customers or fronted by a major anchor customer. It is currently unclear how this future state can or should be realized.

While the satellite servicing sector is working hard to break the chicken-and-the-egg dynamic between servicing providers and users, there have been successful implementations of this use case that organizations are building upon today both conceptually and operationally. The following examples from the past 30 years of space operations highlight the implementation of the in-space upgrade, repair, and replacement of spacecraft components use case into the space enterprise and suggest that these next-generation in-space operations are here to stay.

1.2.1 The Hubble Space Telescope (HST) Servicing Missions

The Hubble Space Telescope (HST), launched in 1990, was designed to be upgraded and repaired by astronauts in space. Many new instruments were installed by astronauts along with the replacement of components that were designed to be modular and replaceable. A regular cadence of upgrades and maintenance were planned for HST; however, not every service was pre-planned (such as thermal blanket repairs). With five servicing missions performed between 1993 and 2009, the HST Servicing Missions accomplished some of the most significant ISAM operations to date. The HST Repair and Upgrade operations differ most notably from likely future missions in that they were all performed by human astronauts and were not fully robotic or autonomous. To summarize the planned serviceability of HST: Class I ORUs were expected to be replaced, one radial instrument and four axial instruments were intended to be replaced with different or upgraded instruments, and several items had limited life and were to be replaced on a schedule, including three Fine Guidance Sensors (FGS), three Rate Sensor Units (gyros), tape recorders, and reaction wheels. Class II ORU's were intended to be replaceable if necessary, and Class III ORU's were potentially replaceable [3].

1.2.1.1 Servicing Mission 1 (SM1) (1993)

Primary purpose: Correct HST's flawed primary mirror optics and address early system degradations.

HST's primary mirror was manufactured to a wrong optical figure, a spherical aberration, causing HST's first images to be blurry. It also experienced a thermal snap of the solar arrays, disrupting observations every 45 minutes. This made SM1 a rescue mission rather than a normal planned maintenance mission. The optical problem was resolved with two instrument replacements. NASA astronauts replaced Wide Field and Planetary Camera 1 (WF/PC 1) with WF/PC2, a built-in corrective optic. The second optics solution was for astronauts to replace an original axial instrument with the Corrective Optics Space Telescope Axial Replacement (COSTAR), a telephone booth sized instrument, which corrected the optical prescription for the other three original axial instruments: the Faint Object Spectrograph (FOS), Faint Object Camera (FOC), and Goddard High Resolution Spectrograph (GHRS). These instrument replacements functionally repaired HST's capability and extended the scientific return of the observatory for decades to come.

Additionally, astronauts replaced HST's solar arrays with new ones from the European Space Agency (ESA) to correct the thermal snap problem. The crew also replaced components that were designed to be modular and replaceable including two rate sensor units containing gyroscopes. The crew performed an upgrade via augmentation by adding a 386 coprocessor to the original flight computer and repaired a thermal problem by adding blankets to magnetometers. HST was also reboosted to a higher orbit during SM1. NASA and ESA saved HST and completed five consecutive days of repairs with remarkably few problems, proving that on-orbit servicing worked [4] [5] [6].

1.2.1.2 Servicing Mission 2 (SM2) (1997)

Primary purpose: Improve scientific capabilities through instrument upgrades and perform general maintenance.

The second Hubble Servicing Mission, SM2, improved the observatory's productivity with new instruments that enhanced its imaging and spectroscopy capabilities. The Space Telescope Imaging Spectrograph (STIS) and the Near Infrared Camera and Multi-Object Spectrometer (NICMOS) were both installed during SM2, replacing GHRS and FOS, respectively. The crew also replaced a Fine Guidance Sensor (FGS); upgraded from an old reel-to-reel Engineering Science Tape Recorder to a modern solid-state recorder (SSR); replaced a Reaction Wheel Assembly (RWA); installed the Optical Control Electronics Enhancement Kit (OCE-EK) to improve FGS performance; replaced a data interface unit; replaced magnetometers; and performed an unplanned installation of improvised blanket patches over degraded blankets [4] [7] [8].

1.2.1.3 Servicing Mission 3A (SM3A) (1999)

Primary purpose: Rapid-response mission to address widespread gyroscope failures.

NASA mission planners originally scheduled SM3A to occur in June 2000 to conduct preventative maintenance to the observatory; however, HST's gyroscopes failed prematurely, necessitating earlier servicing. The first SM3A spacewalk included replacing three rate sensor units, each containing two gyroscopes, and the installation of six battery/voltage temperature-improvement kits. The second spacewalk was centered on installing a new flight computer, a 486-based unit, that was 20 times faster than the previous one, DF-224. The third and final spacewalk included installing a new communications transmitter to replace the one that failed in 1998, along with a second upgrade from tape recorder to SSR [4] [9].

1.2.1.4 Servicing Mission 3B (SM3B) (2002)

Primary purpose: Science-instrument updates and power subsystem restoration.

During SM3B, astronauts installed another new instrument, the Advanced Camera for Surveys (ACS), to replace the Faint Object Camera (FOC), increasing HST's scientific discovery power tenfold. Planned maintenance of the observatory during SM3B also included installation of new rigid, higher power, and more efficient solar arrays, a new Power Control Unit (PCU), and the NICMOS Cryocooler (NCC), which extended the life of the NICMOS instrument after its cryogen was depleted [4] [10].

1.2.1.5 Servicing Mission 4 (SM4) (2009)

Primary purpose: Final refurbishment mission; extend HST's life well into the 2020s.

The final HST Servicing Mission included the installation of two new instruments: the Cosmic Origins Spectrograph (COS), which replaced COSTAR, and the Wide Field Camera 3, which replaced WFP/C2 installed during SM1. Astronauts also performed unprecedented repairs on instruments STIS and ACS. The STIS repair required the removal of a radiator/cover panel held on with 111 non-captive fasteners and the removal and replacement of individual circuit boards. The ACS repair was similar. The STIS and ACS repairs required the development of dozens of new tools and extensive training to perform tasks never intended to be performed on orbit. A full set of batteries was also replaced. New thermal insulation blankets were applied at multiple sites, along with a soft-capture mechanism to enable future robotic capture/deorbit servicing. Finally, all three gyros and an FGS were also replaced, extending the life of HST at least 17 more years to 2026 [4] [11].

1.2.2 International Space Station (ISS) Robotic Servicing

The Special Purpose Dexterous Manipulator (SPDM) is a dual seven-degrees-of-freedom (7-DOF) arm robot that has been in use on the International Space Station (ISS) since 2008. SPDM has been integral for maneuvering external payloads mounted to Flight Releasable Attachment Mechanisms (FRAMs), swapping out compatible ORUs, and other repair activities. SPDM operation is accomplished via ground-based tele-robotics control. A suite of ORU designs exists for various external "black boxes." ISS has the luxury of external storage locations for critical ORUs that are available as needed for changeouts. To date, ORU changeouts have included: Remote Power Control Module, Battery Charge/Discharge Unit, Main Bus Switching Unit, and Camera Light Pan-Tilt Assembly. SPDM has also been used to interact with external payloads, such as repair of science boxes for the Materials ISS Experiment, refueling demonstrations with the Robotic Refueling Mission, and upcoming reconfiguration tasks for the Neutron Star Interior Composition Explorer (NICER) and Coronal Diagnostic Experiment (CODEX) [12].

1.2.3 Orbital Express (2007)

Orbital Express was a mission by the Defense Advanced Research Projects Agency (DARPA) that launched in 2007. Orbital Express demonstrated ORU transfer through a series of autonomous and semi-autonomous operations conducted by two spacecraft in low Earth orbit (LEO): the ASTRO (Autonomous Space Transport Robotic Operations) servicing satellite and the NEXTSat (Next Generation Serviceable Satellite) client satellite. During the mission, ASTRO rendezvoused with NEXTSat, mated, and used a robotic manipulator to install a battery onto NEXTSat. This battery, which was stored on ASTRO prior to installation, provided supplemental power allowing NEXTSat to reduce operational constraints associated with the NEXTSat power system and solar panels. The mission also successfully demonstrated in-orbit refueling between ASTRO and NEXTSat, showcasing the capability to extend the lifespan of operational satellites that are running low on propellant and facing potential replacement. Throughout the rest of the Orbital Express mission, four additional ORU battery transfers between ASTRO and NEXTSat were performed, along with an ORU computer transfer at higher autonomy levels [13].

1.2.4 2026 and Beyond: SpaceLogistics Mission Robotic Vehicle (MRV)

SpaceLogistics' Mission Robotic Vehicle (MRV), which hosts the Robotic Servicing of Geosynchronous Satellites (RSGS) payload developed by DARPA and the U.S. Naval Research Laboratory (NRL), will perform in-space servicing in the GEO belt. Targeted to launch in 2026, with a 10-month or longer transfer to GEO, the mission will perform rendezvous and proximity operations (RPO), capture of unprepared client spacecraft, and installation of Mission Extension Pods (MEPs) using robotic arms. These MEPs will provide a life-extension service via an augmentation operation to their government and commercial clients [14].

RSGS is a flexible robotic platform; therefore, additional tools could be developed, launched to GEO, and integrated onto the platform to enable new types of servicing in the future. Using RSGS's robotic arms, operations such as unfurling stuck deployable antennas or solar arrays could be feasible with the addition of new tools and end effectors. The MRV includes a Northrop Grumman Passive Refueling Module (PRM) within its chemical propulsion system so that a future refueling mission could dock with MRV and refill the hydrazine propellant [15].

1.2.5 OSAM-1

NASA's On-orbit Servicing, Assembly, and Manufacturing 1 mission (OSAM-1) was planned to perform autonomous rendezvous, telerobotic refueling, and orbital relocation on an unprepared spacecraft, Landsat-7. Additionally, OSAM-1 would have hosted the Space Infrastructure Dexterous Robot (SPIDER), a robotic arm intended to assemble a 7-element functional communications antenna. Due to the technical complexity of cutting into the Landsat-7 bus and gaining access to the propulsion system via bespoke dexterous robotic arms and advanced tools, OSAM-1 experienced significant obstacles and was ultimately cancelled. Intended to jump-start the domestic servicing industry, even though OSAM-1 did not launch, the hardware and lessons learned from developing such a "satellite surgery" mission benefit the entire ISAM community [16].

1.3 Value Proposition Considerations

This use case provides value to a client in the cases where upgrading, repairing, or replacing a component is more economical or valuable than a full system replacement or accepting reduced operational capability or lifespan. Speed is also a value factor: if an upgrade, repair, or replacement can be obtained more quickly than a new system can be fielded and brought into operation, that also provides value to the client. While multiple mission effects are achievable through this ISAM operation, the most common applications of the use case were attributed to extending satellite life via repair, upgrading satellite capability, and adding novel capability to a spacecraft, all of which impact mission effectiveness, timeliness, and mission performance parameters.

COSMIC members highlighted a wide range of potential specific applications of this use case, including but not limited to:

- Replacement of failed or degraded components
- Addition of a new mission sensor
- Mechanical deployment anomaly resolution
- Moving, taping down, or replacing loose or lost thermal blankets
- Addition of an external propulsion system
- Removal of Foreign Object Debris (FOD)
- Augmentation of solar power by attaching a new panel and connecting to existing wiring
- Antenna replacement

Since this use case could be deployed in many potential applications and mission CONOPS, it is not possible to make a single value proposition case. However, there are some scenarios in which the use case may provide the most value and lead to more rapid and widespread adoption. Across applications, value added from this use case is always a consideration of the inherent value of the client spacecraft and mission. The non-ISAM scenario we measure against is the cost of launching a new vehicle to the same orbit with the same capabilities as a repaired or upgraded spacecraft would have. Thus, a high-value asset in a difficult-to-reach orbit like GEO may benefit more from servicing than cheaper, replaceable LEO assets.

For a servicing economy to make sense, the servicer needs to be where the clients are. GEO or common LEO slots, for example, are likely to have many potential customers within relatively easy access of a multi-customer servicer. Moreover, a client in a popular orbit is likely paying only a fraction of the overall cost of developing the servicer; thus, their share of cost approaches the cost of the specific instance of the servicing activity only. Orbits with few operational vehicles, like highly elliptical orbits or the Lagrange points, would by contrast need to pay for much or all of the launch and infrastructure cost themselves for a needed servicing operation. This is corroborated by the analysis performed by NASA to identify in-space locations for serviceable deep-space observatories [17].

Augmenting satellites post-launch is the most likely near-term application, with some satellite servicing providers already offering services that can attach backpack-style units to existing satellites to provide new or extended capabilities like propulsion, like Northrop Grumman's MRV [15]. However, to expand the commercial marketplace, multiple companies are needed to provide these types of services.

Value is enhanced with modularity and standards, in which satellite designers adopt singular design approaches to facilitate potential integration with a wide range of service providers. The Consortium for the Execution of Rendezvous and Servicing Operations (CONFERS) develops recommendations for voluntary consensus standards, which are submitted to standards development organizations that include the American Institute for Aeronautics and Astronautics (AIAA) and the International Organization for Standardization (ISO). CONFERS, comprising international members, could provide a starting point for developing or standardizing a unified servicing interface.

Historically, satellites were designed to be self-sufficient for their entire mission because servicing was not available at the time of launch. As that changes, opportunities arise for designers to develop satellites that plan for periodic maintenance, servicing, and even upgrades over a mission lifecycle. Planning ahead for upgrades through a standardized interface or planned modularity allows designers to save upfront cost by removing the need to design overly redundant or bespoke spacecraft. Potential mission designs enabled by modularity could include a system that is launched in an incomplete state if, for example, most of the space vehicle is ready for launch, but a key payload component is behind schedule. Another concept could involve a satellite that "rents out" its upgrade port for mini-payloads or technology demonstration as a way of generating additional revenue.

NASA has hypothesized a similar concept: a persistent-platform that allows for payload swap-out via robotic agents [18]. Additionally, NASA has followed a similar model for external payload attachment to the ISS, and the U.S. Space Force has conceptualized similar designs [19] [20]. A servicing ecosystem also provides a distribution channel for space-made components, and an architecture could be envisioned in which the launch logistics chain is replaced with on-orbit manufacturing and recycling over time.

Lastly, upgrade, repair, and replacement through servicing will be vital for maintaining long-term infrastructure on the Moon and, eventually, Mars. Lunar equipment operating 24/7 has the potential to break down and require repair. Regular, routine resupply missions mean spare parts could be stored in in-space depots, ready to deploy when needed. The premium cost involved in launching material to lunar and Martian destinations incentivizes servicing parts, not systems, when repair, replacement, or upgrade is needed. Demonstrating this capability in more accessible locations like LEO fosters greater confidence for a future in which it will be required on the Moon and Mars.

1.4 Barriers to Adoption

Post-launch integration presents significant technical and demonstration challenges for the backpack-style augmentation use case. Ensuring that hardware connects and functions reliably is difficult to validate under terrestrial conditions—and these challenges are further amplified in the remote environment of space. For successful integration, the client spacecraft must be designed to accommodate a connection, typically by incorporating an interface. As described in Section 1.3, standard interfaces are key to enabling many value propositions, and the lack thereof is a barrier. Currently there are over 30 different connectable interfaces in various stages of development and flight qualification that could support this [21]. In cases like the reboost mission planned for NASA's Neil Gehrels Swift Observatory, which was not initially prepared for such upgrades, even a standardized docking or grappling fixture could offer considerable benefits [22].

Although backpack-style augmentation is often considered "low-hanging fruit" for upgrade opportunities, the spacecraft design implications are complex. Additional mass or modifications can affect the moments of inertia and center of gravity and may introduce thermal variations, all of which must be addressed in future operations.

The primary barrier to adopting these component upgrade and replacement strategies, however, is not technological. Most satellite developers currently do not design for serviceability, meaning there is little market incentive for servicers to invest in the necessary technologies. This creates a classic "chicken and egg" scenario: both the client and the servicer must commit to significant investments for a service-based architecture to be viable, with rewards realized only if both sides actively participate in the ecosystem. These rewards are largely shared between the servicers who are compensated for the service and the operators who benefit from avoiding the cost of a new satellite. In fact, since satellite developers are the likely beneficiaries of satellites needing to be replaced rather than repaired or upgraded, there is market disincentive for satellite developers to move first. Additionally, due to the need for technical information exchange between servicer and client satellite buses manufactures to perform a service operation, competing manufacturers may be reluctant to provide technical information despite non-disclosure agreements being in place. More likely, once satellite purchasers find tangible value in servicing, serviceability provisions will be required in the spacecraft that are procured.

1.5 CONOPS and Gap Assessment Scope

For the purposes of this report, we assume a client/servicer model in which a servicing vehicle maneuvers to a prepared client to be serviced, as opposed to a persistent-platform model in which the client maneuvers to the servicer or a servicing depot. This was chosen based on the assumption that many client spacecraft would lack the extra propellant required for the maneuvers associated with a servicing operation.

This report does not detail the logistics chain responsible for pre-positioning the components, boxes, or tools that the servicer uses to service the client. Additionally, this report does not focus on the "orbitology" of the client and servicer architecture, meaning the orbits of the client, servicer, and servicing operation can be considered to be in any orbit. These considerations are key to any value proposition of this use case.

The technologies required to do spacecraft augmentation versus "satellite surgery" are very different. The latter faces greater technology gaps and is further from realization, whereas augmentation is already happening, with imminent opportunities for expansion. For this reason, the gap assessment sections of this report will primarily focus on the CONOPS of a prepared augmentation operation, in which a servicer installs an external system on a serviceable client spacecraft via compatible interfaces.

2. CONOPS

Following the format of previous COSMIC Use Case reports, a single mission concept of operations (CONOPS) is provided to limit the scope of the gap assessment and recommendations portions of the paper. Per section 1.5, these CONOPS focus on a prepared augmentation servicing.

In some ways, the mission CONOPS applicable to this use case begin well before the spacecraft is launched, during the design and requirements phase. The client spacecraft can be designed to be upgradeable according to a widely adopted architecture leveraging a standardized set of interfaces.

Ideally, upgrading a spacecraft is performed on a logical and pre-planned schedule of routine maintenance, not on demand. Servicing on schedule reduces the downtime for the client, since often servicing on demand requires a component to fail, taking the satellite out of mission before a service call is initiated. Whether servicing is performed on a schedule or on demand, some triggering event occurs in which it is decided that a particular servicer will service a particular client spacecraft.

The servicer will then collect or otherwise already have onboard the required new components for the client vehicle. There is a logistical chain that leads to the servicer obtaining those components, but that is beyond the scope of this report.

The general servicing CONOPS for the remainder of this paper follows the CONFERS On-Orbit Servicing (OOS) Mission Functional Diagram, which shows mission steps from client ingress, rendezvous, proximity, and docking (RPOD) operations, upgrade operations and checkout, and then servicer departure and return to its parking orbit.

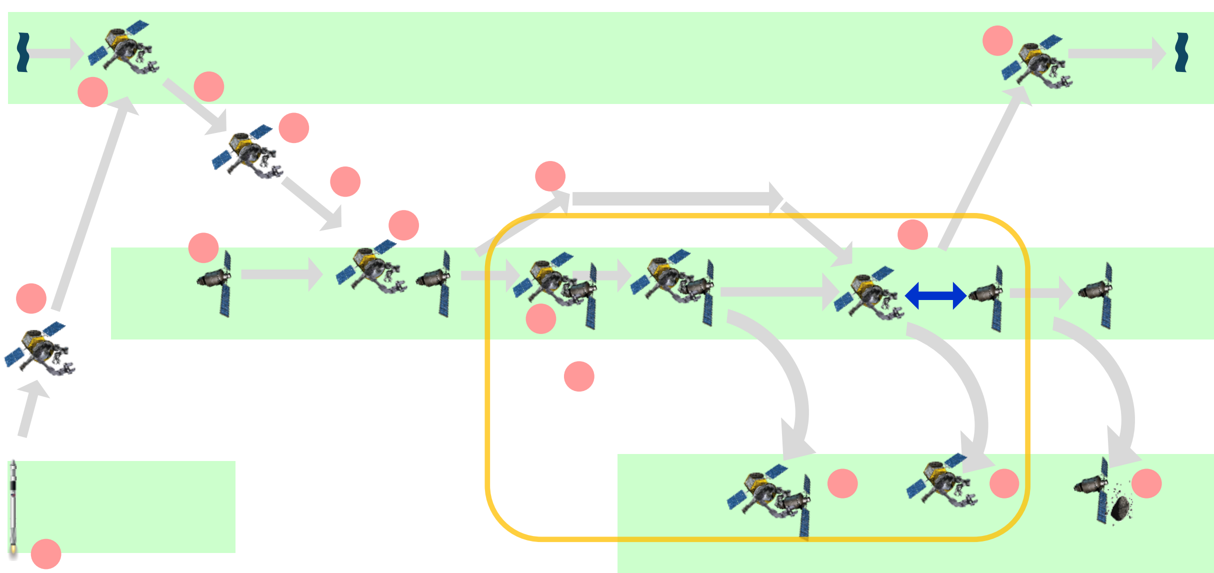

Figure 1. CONFERS On-Orbit Servicing Mission Functional Diagram [9].

This paper focuses on the upgrade operations portion of these CONOPS only, as the RPOD segment and servicer departure segment are identical to those described in the COSMIC GEO Refueling Study [2]. The CONOPS outlined below are focused on augmentation and do not fully address a repair or replacement scenario, though there is significant overlap with repair and replacement servicing operations. This corresponds to the steps outlined in orange in the OOS Mission Functional Diagram. It is important to note that in some cases, the client can remain operational during the service.

Access or Removal of Old Component: Once docked, the servicer must access the interface that will be used for the upgrade operation. In the case of an augmentation, this may involve removing a cover on a prepared interface. In the event of an upgrade via replacement, it may involve the removal of the previous modular component. In this case, the old component would also need to be stored aboard the servicer.

Insertion of Augmentation or New Component: The new component is attached, either in place of the old one or to the prepared augmentation interface.

Checkout: Functional checkout is performed on the client space vehicle and the installed component to ensure that the new component has been installed correctly and is functioning as intended.

Servicer Egress: Servicing vessel undocks and flies away. This may involve flying to a graveyard orbit for disposal of the old component or returning to a parking orbit or a servicing depot.

Client Return to Operations: After checkout and departure of the servicer, the client spacecraft resumes regular operations, now with extended or new capability.

3. Technology State of the Art and Gap Analysis

COSMIC Subject Matter Experts identified four broad categories of key technologies categories required for the realization of this use case and assessed their readiness.

3.1 Guidance, Navigation, and Control (GNC) and Sensors for RPO:

This group includes the following ISAM Technology Taxonomy categories:

- TX0.4.5.2 Rendezvous and Docking Algorithms
- TX04.5.4 Capture Sensors
- TX05.7.3 Active and Passive Sensors
- TX17.1.1 Guidance Algorithms
- TX17.3.5 GNC Actuators for 6-DOF Spacecraft Control during RPOC
- TX17.4.3 Attitude Estimation Sensors

These systems are required for servicer approach and rendezvous with the client satellite. This technology category was thoroughly interrogated as part of the COSMIC GEO Refueling Study [2], which found that these technologies spanned a wide range of maturity and had already been thoroughly demonstrated on orbit. As such, we will not revisit this category in depth in this report, but we do acknowledge its importance to the use case.

3.2 Robotics, Dexterous Manipulation, and End Effectors

This group includes the following ISAM Technology Taxonomy categories:

- TX04.2.3 Small-Body and Microgravity Mobility
- TX04.3.1 Dexterous Manipulation
- TX04.3.2 Grappling Technologies
- TX04.5.5 Capture Mechanisms and Fixtures
- TX04.5.6 Robot Control for Vehicle Capture and Berthing

Relatively simple robotic arms are sufficient for the prepared augmentation aspect of the use case, which would plug in or otherwise connect the augmentation module onto the client satellite. There are a number of systems available that could currently provide this function, such as MDA's Dextre and Orbital Express Demonstration Manipulator System, GITAI's S1, S2, and S10 series of robotic manipulators, and the MRV's RSGS payload, among others. While the hardware technology is readily available, the software and control aspect is less mature as control and movement in a zero-gravity environment, with potential mass shifting and ACS interactions, most likely require maturation.

More advanced end-effectors will be necessary for the "satellite surgery" approach—a process that involves physically altering the existing spacecraft much like a human technician might. These operations could include removing protective coverings and bolts (with provisions for reassembly), cutting, soldering, and conducting high-fidelity inspections. Whether it is a "major satellite surgery" that requires access to the interior of the bus, or "minor satellite surgery" that only manipulates the outside of the spacecraft, tooling represents a crucial technology gap. While the robotic manipulator may be relatively straightforward, its tooling is often complex and must be precisely adapted to the application. Furthermore, a significant consideration is the operation mode of the manipulator—whether it will be controlled locally or via teleoperation. A key challenge to complex robotic tasks is the need for thorough inspection capability that provides the visual access needed for in-situ decision-making and execution. Given the inherent risks associated with physically altering the interior of a spacecraft in orbit, such invasive modifications are likely only considered if maintaining the current spacecraft geometry is essential. Considerations for accessibility in spacecraft design also help enable future modification.

3.3 Modularity and Interfaces

This group includes the following ISAM Technology Taxonomy categories:

- TX04.6.1 Modularity, Commonality, and Interfaces
- TX12.3.1: Deployables, Docking, and Interfaces
- TX12.3.8: Docking and Berthing Mechanisms and Fixtures

Prepared augmentation requires interfaces that, at the least, have mechanical docking points and—in more advanced cases—data and power connections between augmentation payload and client space vehicle.

The ideal interface is one that could be used for a wide variety of augmentations, though with increased interface capability typically comes increased upfront design complexity. For ORU swap-out operations, a standardized interface compatible with the robotic manipulator end effector used to perform the swap-out is an example of an enabling interface.

Implementation of the interface is key to easing servicing operations. At its most capable, it must provide tie-ins to major satellite systems (e.g., power, data), without sacrificing redundancy.

COSMIC's "United States ISAM Interfaces Ecosystem 2025 Report" details a number of high-TRL technologies available that could fulfill this need, including Lockheed Martin's ASPIN, Starfish Space's Nautilus (TRL 7), and Sierra Space's Orbital Express Capture System (TRL 9), among others [23]. There are also interfaces capable of supporting both a mechanical dock and data and power connections like Oceaneering's Gold-2 (TRL 9) used on ISS and Sierra Space's Structural Power and Data Port (TRL 6) that will fly on RSGS later in 2026. Convergence among the ISAM community on which standardized interfaces should be developed is a critical next step to enable robust upgrade applications that can support many different client spacecraft.

3.4 Environmental Sensors and Verification

This group includes the following ISAM Technology Taxonomy categories:

- TX08.1.2 Electronics
- TX08.3.4 Environment Sensors
- TX12.3.4 Reliability, Life Assessment, Health Monitoring
- TX 12.3.5 Certification Methods

Sensor suites that can monitor spacecraft health and performance are required to determine when servicing is needed and whether the service has been successful. The technologies needed for this task are a routine part of any spacecraft, but the implementation for upgrade through prepared augmentation requires unique considerations to ensure that an augmentation connects properly and performs as expected.

The current approach largely depends on pre-mission modeling, systems engineering analyses, and contractual interface control documents. Without standardized interfaces, shared data environments, or real-time on-orbit characterization capabilities, these assessments frequently rely on incomplete or outdated information, leading to secondary effects—such as thermal changes, attitude control impacts, and power budget shifts—being discovered late and addressed reactively at significant cost.

The most critical consideration is commonality of interfaces across systems. For other upgrade characteristics like size, weight, and power, a general focus on tolerance and ratings review is typically sufficient. However, proper assessment requires information from the original bus manufacturer to understand impacts on the attitude control system, and if the upgrade draws power from the host, available payload power. This work falls to GNC engineers and power balance engineers, often requiring joint effort between the builders and operators of both the client spacecraft and the servicer spacecraft.

While these tasks represent normal spacecraft engineering activities, the challenge lies in effective collaboration between parties. A potential solution is for a third party to provide a service that simplifies importing data from both sources and analyzing the combined vehicle stack, streamlining the integration process and reducing the risk of late-stage discoveries and costly reactive modifications.

Preparation requires extensive ground testing, interface validation, and high-fidelity simulation of the full on-orbit sequence before initiating the servicing operation. This includes characterizing the target spacecraft, defining clear success criteria, stress-testing failure modes, and confirming mechanical, power, and data compatibility on the ground. Operational procedures and contingency plans must be established and rehearsed. A representative demonstration of the upgrade sequence CONOPS should be performed on the ground, working through all requisite stages: inspect, approach, engage, upgrade, and separate. Equally important is developing a well-defined fault response describing how to react during potential anomalies. Benchmarks comparing the legacy system against the upgraded system should be established, with full ground demonstration preceding in-space validation.

Drawing from heritage programs like HST, proven approaches include maintaining ground testbeds with all necessary electrical and mechanical interfaces to attach proposed upgrades, performing fit checks, and testing integration with avionics and software down to commanding from the Mission Operations Center (MOC). Most companies maintain "FlatSats"—representative configurations of in-flight avionics and flight software that can connect to their MOC—providing high confidence through comprehensive test campaigns. For physical attachment, using standard interfaces with verified interoperability, ensuring any copy of one side will fit and work with any copy of the other side, is critical for success.

4. Demonstration Infrastructure State of the Art and Gap Analysis

There is a current lack of reliable mechanisms to validate that upgrades will perform as expected on orbit. Validation relies on a fragmented combination of ground-based simulation, hardware-in-the-loop testing, and limited flight heritage. Without robust, accessible demonstration infrastructure, there is no repeatable way to confirm that an upgrade will connect and function properly in the actual space environment before operational deployment. The solution requires ground facilities that accurately mimic all interfaces and electrical, mechanical, and data infrastructure, along with either standardized interfaces that can be physically tested both on the ground and ideally in orbit, or flight spares of unique interfaces for ground testing.

Drawing from historical experience with programs like HST and ISS, rigorous validation processes are essential. NASA's Johnson Space Center (JSC), NASA's Goddard Space Flight Center (GSFC), and Lockheed Martin maintained teams dedicated to ensuring tools, ORUs, and permanent components would fit on orbit, sometimes requiring physical fit-checking of tools and ORUs to vehicles before launch. This included clear engineering understanding of tolerancing under various thermal conditions, strict adherence to power voltage and data interface standards, and functional testing of command and telemetry with flight-like surrogates. Modern digital-twin approaches can leverage detailed 3D scanning and authoritative Computer Aided Design (CAD) models of all system interfaces prior to launch, enabling digital fit-checks with new components to build confidence.

Validation should occur across digital, physical, and in space domains. Digital demonstration is cheap and easy but offers limited confidence. Infrastructure—in the form of specialized software products for modeling contact and motion dynamics, electrical interactions, and even thruster plume interactions—is well established. Ground-based infrastructure for demonstrating CONOPS, vision systems, motion dynamics, and robotic interaction is available in the form of float-table facilities, thermal vacuum chambers, and interacting robot facilities. As noted above, electrical and radio frequency interaction demonstration is missing, but this is only due to the lack of common interfaces and the fact that spacecraft are currently not designed with future service in mind.

Orbital demonstration infrastructure is critical especially for first of its kind services, proving out standardized interfaces and upgrades, and for the combined space environment. Orbital infrastructure is currently limited to a single persistent-platform, the ISS, which is scheduled for decommissioning, making this the key identified demonstration infrastructure gap. The ISS has served as a valuable testbed—for example, Kall Morris, Inc. demonstrated capabilities via NASA's Astrobee system in a microgravity environment that allowed free-flyer operations testing without propellant expenditure, which is crucial for developing in-space servicing technologies. However, the ISS is scheduled for decommissioning in 2030, and while its external environment is already utilized for programs like the Space Systems Command Space Test Program, a fundamental gap remains in the industry's infrastructure.

4.1 Recommendations

Several approaches are recommended to close this gap. These include missions similar to Orbital Express, in addition to demonstrations using low-cost existing buses that fly to a persistent-platform for servicing through a progressive validation approach that builds confidence through flight. This requires developing purpose-built demonstration satellites with standardized augmentation interfaces, executing graduated on-orbit experiments that advance from inspection to physical attachment to functional augmentation, and making resulting data and lessons learned accessible across government and commercial stakeholders. Apart from demonstrations that prove out operations and technology, demonstrations that include follow-on missions and prove out a return-on-investment for both the servicer and client organizations are equally as important to the ISAM ecosystem.

4.2 Centralized Servicing Ground Testbed

On the ground, a centralized facility equipped with replicas of commonly used grapple fixtures (such as those on ISS modules and Cygnus spacecraft), passive FRAMs, berthing devices for the Japanese Experiment Module-Exposed Facility (JEM-EF), OneWeb docking plates, and other in-use docking and ORU fixtures would enable companies to test their grapple and docking device designs in simulated 6-DOF zero-gravity conditions. This facility would provide a standardized environment for validation before costly on-orbit demonstrations, perform validation of both the pose estimation and contact dynamics portion of the use case CONOPS, and perform fit checks, ensuring that sensor suites and electronics can detect and correctly operate with an augmentation.

4.3 On-Orbit Validation

The core challenge is that the space industry currently lacks persistent, accessible, and affordable on-orbit demonstration platforms necessary to mature critical technologies for space domain awareness, in-space servicing, and orbital sustainability. While various government and commercial initiatives show promise—such as NASA's Fly Foundational Robots program to test requisite technology with the Motiv Robotic Payload—the absence of dedicated, reusable orbital testbeds and standardized demonstration platforms continues to hinder technology maturation and validation at operationally relevant timescales [24].

ISS demand already exceeds its availability and, with it slated for disposal in 2030, new orbital test facilities are required. NASA's Commercial LEO Destinations (CLD) could offer these services once established and close this infrastructure gap. However, if humans are included in the testing loop, cost and complexity will be significant due to ensuring compliance with human-rated safety requirements. Arkisys' Port—an uncrewed platform—and similar robotic persistent-platform models could be leveraged to avoid constraints associated with astronaut activity.

A testbed should function as the industry's proving ground, bridging the gap between ground-based test and analysis and operational confidence before upgrades are deployed on actual client spacecraft. This requires providing standard or semi-standard interfaces—including physical, thermal, power, and data connections—along with sufficient capability to test upgrade functions, such as specific orientation or pointing requirements. It must contain potential debris, maintain station-keeping and refueling capabilities, communicate effectively, and evolve by upgrading its own hardware. The baseline should mirror ISS capabilities, including external WiFi, Ethernet, power, and fiber-optic connections at demonstration ports, with dexterous robotics available for testing operations. Critical functionality includes read/write capabilities with built-in unit tests for upgrades—for example, a robotic arm should be able to spin around, operate its end effector, and report completion of unit tests back to the testbed. The testbed should also provide detailed telemetry to capture impacts on the Attitude Control System and power systems, enabling improved modeling for future platform responses.

Publication and documentation of lessons learned during orbital technology maturation demonstrations is vital.

5. Policy and Regulation Current State and Future Recommendations

COSMIC subject matter experts identified key policy and regulation issues that impede the widespread realization of this use case. While servicing operations have been performed on orbit, this section details recommended adjustments needed to domestic and international policy to support the bourgeoning ISAM ecosystem.

5.1 Overview

Beyond technological development and appropriate testing infrastructure, policy that regulates in-space upgrade, repair, and replacement of spacecraft components is equally important to developing and scaling this use case. Due to the nascent nature of implementing a servicer-client architecture with embedded ISAM capabilities, domestic and international regulatory and policy measures are not robust. Much of the policy and regulation gaps found by COSMIC's Policy & Regulation (PR) focus area overlap with other identified ISAM use cases and can be found in the COSMIC GEO Refueling Study [2]. However, for the upgrade and repair of spacecraft capabilities, some unique challenges exist.

5.2 Recommendations

5.2.1 Liability Policy

As with other ISAM use cases, physical contact of two separate spacecraft is required to achieve a physical or functional repair or upgrade. Additionally, most near-term upgrade and repair servicing operations will be performed on unprepared clients that have not been designed to be altered after launch. Liability in this case is complex to define and requires the drafting of robust agreements between the servicer and client organizations due to the lack of national and international policy regulating these operations. The procedure to create robust contracts to cover liability often requires immense resources, which can be particularly burdensome on small start-up companies focused on technology maturation and demonstration.

Unique to the upgrade, repair, and replacement of spacecraft components use case, the alteration of the client, whether through component replacement or augmentation, leaves a lasting change to the client. For a potential future malfunction related to the components or systems being altered or augmented, liability needs to be defined between the servicer and the client. In the case of augmentation, the servicer provides the client with a "leave-behind capability" which changes the spacecraft's operating procedure. Once the augmentation is performed and validated, the servicer and client must have robust agreements covering future malfunctions related to the operation. Therefore, action should be taken to better define both domestic and international policy related to liability for ISAM operations, and particularly for cases of altering a spacecraft's hardware in orbit and attaching external boxes via augmentation.

5.2.2 Developing and Promoting the Use of Open Standards

As mentioned in sections 1.3 and 1.4, standards are key for enabling interoperability between servicer and client spacecraft and streamlining in-space operations. The implementation of standards can fast track aspects of spacecraft design. Thanks to the open-source architecture of interoperability standards, policy, particularly with regard to liability associated with actions involving the standard, can be more easily defined. While CONFERS is developing recommendations for consensus standards, U.S. government agencies hold interface designs from previous and current ISAM missions that could be made into standards. Using policy to release previously developed interfaces into the open market via open standard development could help stimulate the ISAM ecosystem.

To alleviate pressure on servicing organizations that are struggling to find clients due to the lack of satellite interoperability, the implementation of standards on client buses and designing clients to be serviceable via standard interfaces could be incentivized. However, incentivizing standards would require a grading rubric justifying said incentives, and defining the incentive could lead to market favoritism. Generally, policy action should be focused on pushing currently existing interfaces into the public domain.

5.2.3 Insurance Considerations

Currently, the U.S. does not require insurance covering an in-space asset, liability, or third parties. Additionally, high premiums discourage smaller organizations from purchasing insurance due to thin margins and nascent business cases. However, servicers and clients involved in an ISAM operation, particularly a mission involving a new startup organization, can help draw investors if their spacecraft are insured, by buying down risk associated with the operation that digital twins, test beds, and simulations cannot. Policy that requires either servicers and/or clients to be insured or policy that reduces insurance premium costs could be adopted to facilitate the flow of investors into the startup ISAM community.

5.2.4 Multinational Framework

To develop a robust international ecosystem of ISAM services, international space law will require either supplementation or streamlining to ease the regulatory burden on governments and industrial organizations. As defined in the COSMIC GEO Refueling Study, an international framework for ISAM should be developed to facilitate items such as registration, authorization, supervision, and liability [2]. This framework can provide industry with certainty for investment by ensuring that international ISAM operations are safe, sustainable, predictable, and well regulated.

6. Integrated Assessment and Recommendations

This report interrogates the use of ISAM capabilities to modify spacecraft after launch through three main approaches: upgrade (improving or adding new capabilities), repair (restoring original functionality), and replacement (swapping components to restore or extend designed capabilities). Upgrade is considered the most valuable option as it expands mission capability, while repair and replacement are most useful early in a mission—after which failed components are likely outdated compared to current technology. In practice, repairs and replacements often involve upgrades simultaneously, such as replacing a broken processor with a more powerful modern version, allowing spacecraft to maintain contemporary capabilities rather than perpetuating obsolete technology.

The implementation of these modifications can take three primary forms: "satellite surgery" (manipulating a vehicle's interior), modular component swap, and augmentation (attaching external equipment). Augmentation is significantly simpler from an engineering perspective and shows the most near-term promise. An example of facilitating augmentation operations is designing spacecraft with standardized interfaces—conceptualized as "USB for space"—that would allow plug-and-play upgrades similar to computer peripherals. This standardization would eliminate recurring engineering costs, enable a single servicing architecture to serve multiple satellites, and potentially support an orbital depot system for storing ORUs. The value proposition varies significantly based on factors like orbit accessibility and client spacecraft value, with high-value assets in difficult orbits like GEO potentially benefiting more than easily replaceable proliferated LEO satellites, and orbits with many operational vehicles offering better economics through shared servicing infrastructure costs.

Despite the technical feasibility of augmentation approaches already being demonstrated by providers offering backpack-style units for capabilities like propulsion, significant challenges remain for widespread adoption. Post-launch integration presents difficulties in ensuring reliable hardware connections and functionality in the remote orbital environment, with added complications from mass, thermal, and center-of-gravity changes affecting spacecraft operations. The more advanced "spacecraft surgery" approach requires sophisticated end effectors and tooling for operations like removing bolts, cutting, and soldering, along with disposal solutions for removed components. However, the primary barrier is not technological but economic and cultural: most satellites are not currently designed for serviceability, creating a chicken-and-egg problem where neither clients nor servicers have market incentives to invest in the necessary infrastructure without commitment from the other party, making demonstration of a viable servicing ecosystem essential for realizing this use case.

6.1 Recommendations

6.1.1 Increased Access to Demonstration Opportunities

There is not a technology development shortfall for this use case; rather, additional demonstrations are needed to build the confidence of satellite developers and acquisitions. This is an essential step to increase serviceability demand which will in turn incentivize satellite developers to consider serviceability in satellite design.

COSMIC recommends investment in ground facilities capable of serving as facsimiles of client vehicles, as well as one or more in-space testbeds designed to rapidly and cheaply mature ISAM technologies such as those required for this use case.

6.1.2 Incentivize Satellite Design for Upgradeability

The primary technical challenge impeding this use case is not the servicing technology itself, but rather designing for upgradeability that can reliably be performed through automation. However, the more fundamental obstacle is the business case. High-value assets like ISS, HST, and the James Webb Space Telescope (JWST) could justify dedicated servicing missions because their sunk costs exceeded billions of dollars, but most satellites currently in orbit cannot justify servicing. Without a multi-mission servicing architecture and depot infrastructure, servicing becomes economically viable for only a small fraction of existing satellites, leaving the average satellite without a justifiable upgrade path.

Successful augmentation has already been demonstrated through programs like HST, ISS, and Orbital Express. The principle has been strongly validated; now the focus should shift to including design requirements for augmentation on new vehicles from the outset. **COSMIC recommends that all future GEO satellites require provisioning for servicing in their requirements.** Existing hardware, procedures, and lessons learned from past and future demonstrations should be leveraged and shared with broader industry. Continuing a track record of success and value-added operations will continue to increase the appetite for augmentation capability in near-term systems, which in turn will open up opportunities for more complex servicing operations to be adopted. Standardization of hardware and processes will develop along with the servicing ecosystem.

7. References

[1] COSMIC, "COSMIC Publicly Released Products," [Online]. Available: https://cosmicspace.org/resources-2/cosmic-released-products/. [Accessed 23 06 2026].

[2] COSMIC Consortium, "A Cross-Disciplinary Study of On-Orbit Refueling For Geostationary Satellites," 25 November 2025. [Online]. Available: https://cosmicspace.org/wp-content/uploads/2025/12/COSMIC-E01-C002-2025-A-GEO-Refueling-Use-Case.pdf.

[3] NASA, "Astronaut Missions to Hubble," 25 November 2025. [Online]. Available: https://science.nasa.gov/mission/hubble/observatory/missions-to-hubble/.

[4] R. Talcott, "A history of service," astronomy.com, 18 May 2023. [Online]. Available: https://www.astronomy.com/science/a-history-of-service/. [Accessed 02 June 2026].

[5] NASA, "Hubble Servicing Missions Timeline," [Online]. Available: https://science.nasa.gov/mission/hubble/overview/hubble-timeline/hubble-servicing-missions-timeline-full-text/. [Accessed 02 06 2026].

[6] NASA, "Servicing Mission 1," 16 April 2024. [Online]. Available: https://science.nasa.gov/mission/hubble/observatory/missions-to-hubble/servicing-mission-1/.

[7] ESA, "Servicing Mission 2," [Online]. Available: https://esahubble.org/about/history/servicing_mission_2/. [Accessed 02 06 2026].

[8] NASA, "Servicing Mission 2," 16 April 2024. [Online]. Available: https://science.nasa.gov/mission/hubble/observatory/missions-to-hubble/servicing-mission-2/.

[9] NASA, "Servicing Mission 3A," 16 April 2024. [Online]. Available: https://science.nasa.gov/mission/hubble/observatory/missions-to-hubble/servicing-mission-3a/.

[10] NASA, "Servicing Mission 3B," 28 February 2025. [Online]. Available: https://science.nasa.gov/mission/hubble/observatory/missions-to-hubble/servicing-mission-3b/.

[11] NASA, "Servicing Mission 4," 17 June 2025. [Online]. Available: https://science.nasa.gov/mission/hubble/observatory/missions-to-hubble/servicing-mission-4/.

[12] S. Aziz, "Development and verification of ground-based tele-robotics operations concept for Dextre," Acta Astronautica, 2013.

[13] R. B. Friend, "Orbital Express Program Summary and Mission Overview," The Boeing Company, Huntington Beach, CA, 2008.

[14] Northrop Grumman SpaceLogistics, "SpaceLogsitics," [Online]. Available: https://www.northropgrumman.com/what-we-do/space/space-logistics-services. [Accessed 28 April 2026].

[15] L. Bernstein, "Northrop Grumman's First MRV Readies for Summer Launch to Expand the Space Servicing Toolkit," 19 May 2026. [Online]. Available: https://www.satellitetoday.com/technology/2026/05/19/northrop-grummans-first-mrv-readies-for-summer-launch-to-expand-the-space-servicing-toolkit/.

[16] NASA, "On-orbit Servicing, Assembly, and Manufacturing 1 (OSAM-1)," 23 March 2026. [Online]. Available: https://www.nasa.gov/mission/on-orbit-servicing-assembly-and-manufacturing-1/.

[17] S. J. L. Harvey J. Willenberg, "Site Selection and Deployment Scenarios for Servicing of Deep-Space Observatories," in *IEEE Aerospace Conference*, Big Sky, MT, 2001.

[18] W. R. e. a. Doggett, "Near-term Persistent Platform Orbital Testbed: Three Candidate Architecture Options," in *AIAA ASCEND Conference*, Virtual, 2020.

[19] NASA, "External Payloads Proposer's Guide to the International Space Station, SSP51071 Baseline 2017," NASA Goddard Space Flight Center, Greenbelt, MD, 2017.

[20] P. C. L. N. B. L. H. R. M. R. a. R. E. Leonard A. Plotke, "In-Space Developmental Test Persistent Platform for US Space Force," in *AIAA SciTech*, San Diego, CA, 2021.

[21] R. R. a. N. G. David Barnhart, "Dispelling the Myth of the Universal Interface: Results and Inferences From an Evaluation of In-space Connectable Interfaces," in *AIAA SciTech*, Orlando, FL, 2026.

[22] Katalyst Space Technologies, "Katalyst Develops Design for NASA to Rescue $500M Space Telescope from Uncontrolled Reentry," [Online]. Available: https://www.katalystspace.com/post/katalyst-develops-design-for-nasa-to-rescue-500m-space-telescope. [Accessed 28 April 2026].

[23] A. Franklin, "United States ISAM Interface Ecosystem 2025 Report," The Consortium For Space Mobility And ISAM Capabilities, 2025.

[24] NASA, "NASA's Fly Foundational Robots Demo to Bolster In-Space Infrastructure," NASA Goddard Space Flight Center, 2 December 2025. [Online]. Available:

https://www.nasa.gov/centers-and-facilities/goddard/nasas-fly-foundational-robots-demo-to-bolster-in-space-infrastructure/.

[25] R. Talcott, "A History of Service," 18 May 2023. [Online]. Available: https://www.astronomy.com/science/a-history-of-service/.