Beyond Earth – In-space Logistics & Servicing

CATAPULT Satellite Applications

Technical Considerations for Serviceable Spacecraft

November 2025

Author: Gary Cannon

Co-author: Yige Sun

We work with UKRI Innovate UK

Contents

Document Revision History

Revision	Modification	Modified by	Date
0a	Initial draft	G. Cannon	5/2/25
V1	Incorporated input by co-author	G. Cannon	10/11/25

Contributions

This paper was made possible by technical contributions from the following organisations:

Aphelion Industries Ltd

TTP plc

1. How do we Enable the Future of Space?

1.1. Vision: The Future of Spacecraft Design and Operation

The future of services from space, space exploration, and satellite operations is poised for transformation, driven by emerging technologies, increasing commercial engagement, and a growing focus on sustainability. While traditional spacecraft designs—typically single-use and non-serviceable—still dominate current missions, there is a growing recognition of the potential benefits offered by modular, reusable, and serviceable systems. This paper sets out a vision and a technically feasible pathway toward realising these next-generation spacecraft architectures. By exploring the design considerations, enabling technologies, and standardisation efforts needed to support serviceable spacecraft, this work aims to guide the space sector in making this transition both practical and achievable.

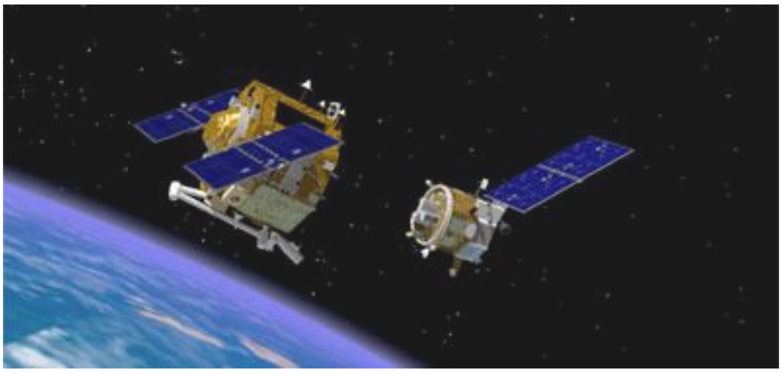


Image Credit: Boeing

Serviceability presents a promising opportunity to reduce mission costs, enhance operational flexibility, and promote more sustainable use of space and the infrastructure therein—if it can be implemented affordably and reliably. For high-value assets such as geostationary satellites, which are characterised by long lead times, high capital investment, and strategic importance, the ability to maintain, refuel, or upgrade systems in orbit could significantly shift mission economics. While recent developments in robotic servicing and refuelling technologies suggest technical feasibility, the central challenge remains: how can we design serviceable spacecraft architectures that deliver cost savings, enable modular upgrades, and support long-term sustainability in a commercially and operationally viable way?

As the demand for reliable, long-term satellite services grows, spacecraft designed for serviceability will become a cornerstone of the industry. A vision for the future must embrace such capabilities, ensuring satellites can be efficiently maintained and upgraded to provide sustained operational capability and reducing the frequency of costly replacements. Such an approach will not only improve mission resilience but also enable more sustainable and cost-effective space operations.

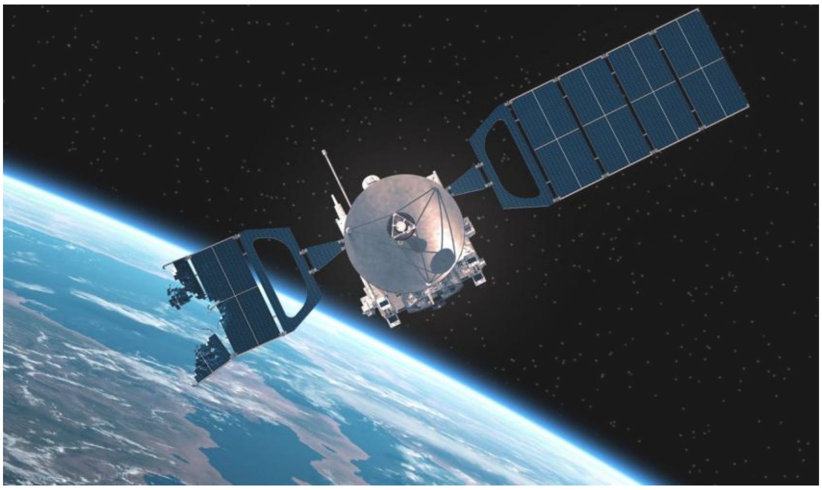
1.2. The Case for Modular and Serviceable Spacecraft

The rationale for designing modular and serviceable spacecraft is multifaceted. From an economic perspective, the ability to replace or upgrade individual components and subsystems/payloads or refuel, rather than decommissioning an entire spacecraft, enables operators to maximise the value of their assets, reduce operating costs, and capture new revenue opportunities. Modular systems also enhance mission adaptability, allowing operators to incorporate new technologies quickly or respond to emerging needs without ordering, designing, building, and launching entirely new spacecraft.

From a sustainability standpoint, serviceable spacecraft help mitigate space debris and the ever-increasing population of the GEO graveyard by increasing the lifetime of orbital assets. There is also growing concern about the effect that de-orbiting spacecraft have on Earth's atmosphere[i]. Servicing spacecraft or replacing their payloads also helps to mitigate the energy/carbon cost of launch as only the payload needs launching rather than the entire spacecraft (platform+payload). On-orbit servicing can facilitate repairs, component or subsystem updates, and system refurbishments, reducing the frequency of replacement launches and conserving valuable resources.

Use Cases

- The Large Deployable Antenna on Viasat-3 F1 did not deploy, leading to a $400 million insurance claim. The satellite itself reportedly cost $750 million and took 4 years to build
- Inmarsat 6 F2 had a power system failure that led to a total loss of the satellite, resulting in a £350 million claim
- The Hubble Space Telescope. With no servicing, this entire mission would have failed, with an insurmountable loss to science and inspiration
- Northrop Grumman MEV extending the life of two Intelsat missions by 6 years, allowing Intelsat to defer the cost of replacement and resulted in cost savings of around $65 million
- An unnamed company procured a smallsat to provide EO data from LEO. 6 months into the mission, contact with the satellite was lost. As the company's business model relied on data from that satellite, they had to order and wait 1.5 years for a new satellite to be provided



In these cases, the magnitude of the loss of a space asset is so high and the time to replace them so long, that the case for in-orbit servicing and repair is highly compelling and in particular for the operators and insurers.

Furthermore, a modular approach fosters interoperability, encouraging standardisation across spacecraft components and servicing mechanisms. This, in turn, promotes collaboration across governmental and commercial space organisations, paving the way for a more robust and cooperative space infrastructure.

Finally, studies are taking place to assess the effect of burning up satellites in the atmosphere is having on the chemistry of the atmosphere. Early research shows that substances produced when satellites ablate are interfering with aerosols in the atmosphere. Serviceable spacecraft could go some way to mitigating this.

1.3. Scope and Objectives of this Concept Paper

This concept paper aims to explore the technical considerations, design principles, and operational frameworks necessary for realising serviceable spacecraft. Contributions from experts across various disciplines—including spacecraft engineering, robotics, propulsion, materials science, and mission operations—have been crucial in shaping a comprehensive understanding of the challenges and opportunities in this field.

The objectives of this concept paper include:

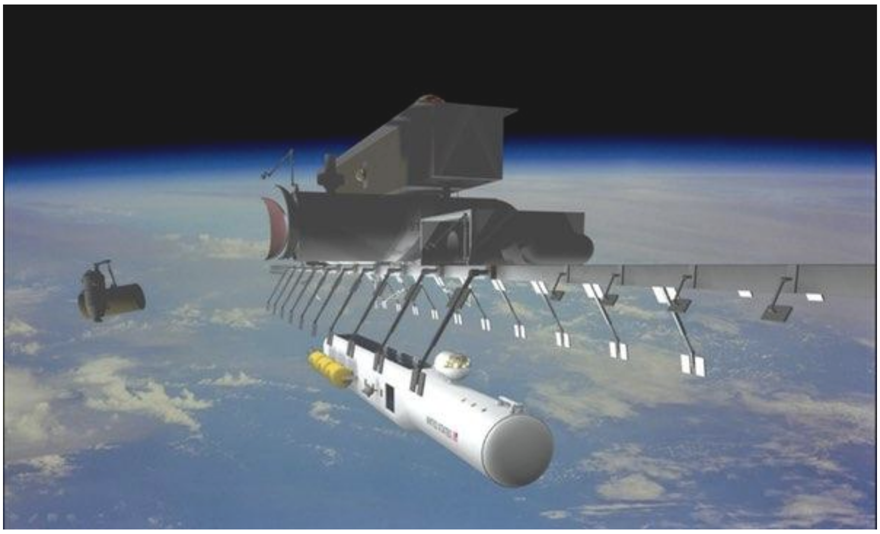
- Identifying key design principles that facilitate spacecraft serviceability and modularity
- Assessing current and emerging ISAM technologies that support on-orbit servicing, repair, and upgrades
- Propose a system architecture for a serviceable spacecraft

By integrating expert insight, this paper establishes a foundational framework for advancing serviceable spacecraft from a technical standpoint, enabling extended operational lifetimes, enhanced sustainability, improved mission performance and ultimately shaping the next generation of space systems.

Given the diversity of space systems technology, financial details are hard to determine or acquire. As such, this paper does not consider specific economic cases for serviceable spacecraft.

2. Who Wants Serviceable Spacecraft? What are the Applications?

As the demand for flexible, sustainable, and cost-effective space infrastructure grows, users across commercial, scientific, and defence domains will seek alternative solutions for spacecraft platforms. Modular, upgradeable, and serviceable platforms can answer this. The capabilities of such systems respond to a shared set of needs: reducing launch costs (and the resources used therein), enabling faster technology refresh cycles, supporting high-throughput data applications, mitigating space debris and atmospheric concerns.



A key user requirement is in-orbit testing and demonstration of new components, materials, and systems. Conventional ground-based simulation environments—thermal vacuums, vibration rigs, and radiation chambers—can only approximate the conditions of space. A modular, in-orbit testbed that allows new hardware to be slotted into standardised receptacles or platforms offers users a path to validate performance under actual space conditions. Agencies like ESA and companies like Nanoracks have already started deploying such platforms on the ISS and for free-flyers, but there is a growing interest in scalable, commercial equivalents.

Another major driver is in-orbit servicing, assembly and manufacturing (ISAM). As these technologies mature, users anticipate building satellite chassis in space from modular components. This unlocks several advantages: structures no longer need to survive the stresses of launch, allowing them to be built lighter, more flexibly, and potentially from in-situ resources or recycled parts. This translates into lower material use per unit, reduced launch mass, and thus lower costs. It also enables distributed spacecraft architectures, where functions are separated across multiple modular elements rather than crammed into a single bus.

Closely tied to this is the demand for hardware upgradeability and lifecycle extension. Satellite operators—especially in defence, communications, and Earth observation—are increasingly looking to decouple long-lived infrastructure (like power and propulsion) from rapidly advancing technologies (such as processors, sensors, and cryptographic units). Modularity allows for in-orbit servicing missions to upgrade specific elements rather than replacing entire systems, reducing capital expenditures and enabling faster response to market or mission shifts. For example, future encryption upgrades may demand secure hardware changes—something infeasible with today's highly integrated, non-serviceable spacecraft.

Furthermore, users are recognising the value of edge compute and orbital data centres. With space-based sensors generating terabytes of imagery and telemetry daily, downlink bottlenecks are becoming a critical limitation. Orbital compute platforms, built from modular, upgradeable components, can store, process, and even triage data before it's sent to Earth—reducing latency, enabling onboard AI/ML, and increasing scientific and commercial returns. NASA's investigations into onboard AI processing, and companies like Axiom, Ramon.Space, and Lonestar building orbital servers, point to this rapidly growing need.

These advancements hinge on robust interconnect systems. Whether electrical, optical, or fluidic, these connections must be reliable, reconfigurable, standardised, and serviceable—able to handle harsh radiation, vacuum, and thermal cycles. Just as USB and PCI standards revolutionised modularity on Earth, space needs interoperable plug-and-play solutions. CONFERS, BSI, and NASA's OSAM initiatives are beginning to develop such standards, but broader adoption is needed.

Finally, sustainability is now a customer need[ii], not just a compliance metric. Modular, serviceable satellite platforms aim to eliminate space debris by enabling component reuse, aggregation of defunct hardware, and mission extension. This aligns with global policy movements such as the UN's Long-Term Sustainability Guidelines for Outer Space Activities and increasing pressure from financiers, insurers, and regulators to adopt responsible mission architectures.

In summary, stakeholders across the community envision a shift toward flexible, serviceable, and sustainable space systems. This vision requires an ecosystem of interoperable technologies, modular architectures, and in-orbit logistics that collectively unlock lower costs, greater responsiveness, and a more circular space economy.

2.1. Example Missions

DARPA/Northrop Grumman – RSGS (Robotic Servicing of Geosynchronous Satellites) or "MRV"
The RSGS mission aims to provide in-orbit servicing including inspection, refuelling, and hardware upgrades of GEO satellites. This is a strong proof-of-concept for modular satellite servicing, particularly for commercial and defence customers requiring high uptime and resilience.

Maxar Technologies – Space Infrastructure Dexterous Robot (SPIDER) - CANCELLED
Part of NASA's OSAM-1 mission, SPIDER was planned to demonstrate robotic in-orbit assembly of large modular structures like antennas. Whilst deemed critical for future space-based communications platforms and telescopes that can't be launched fully assembled, the project was cancelled due to significant delays, cost overruns, and technical challenges.

Nanoracks – Bishop Airlock & Outpost Program
Initially deployed on the ISS, Bishop offers a testbed for modular in-orbit experimentation. Nanoracks' Outpost program aims to convert upper stages and retired satellites into functional, modular platforms for experimentation, storage, or habitation.

Ramon.Space / Lonestar / Axiom – Orbital Data Centres
These missions involve deploying compute/storage units to perform in-space data processing. Their goal is to reduce downlink demand and process data at the edge, ideal for Earth Observation or deep-space missions where latency and bandwidth are limiting factors.

Orbit Fab – In-Space Refuelling Infrastructure
Orbit Fab is developing standard refuelling interfaces (RAFTI) and fuel depots for satellites. These enable satellite lifetime extension and support a serviceable modular spacecraft economy.

ESA/Thales Alenia Space – EROSS Project (European Robotic Orbital Support Services)
EROSS demonstrates rendezvous and robotic servicing of modular platforms in LEO and GEO. It supports replaceable payload modules and shows Europe's commitment to building interoperable, sustainable spacecraft servicing infrastructure.

2.2. Provenance of Requirements

The demand for serviceable spacecraft is coming from multiple stakeholder groups, each with distinct motivations, but the strongest drivers right now are:

Primary Drivers

Satellite Operators: Operators (commercial and defence) want to extend asset life, reduce costs, and add flexibility. Servicing allows them to:

- Upgrade payloads or compute power mid-life
- Replace aging components without full satellite replacement
- Refuel or reposition satellites instead of deorbiting
- Get better return on capital-intensive infrastructure

This is especially important for high-value assets in GEO, where the cost of replacement is in the hundreds of millions of dollars range, and LEO constellations looking to reduce replacement cycles.

Strategic Enablers

National Space Agencies like NASA and ESA:

- Aim to maximise long-term value from costly assets through extended lifetimes and sustainable operations
- Respond to increasing political and societal pressure to reduce space debris and improve the efficiency of public investment
- View modular and serviceable spacecraft as essential for ambitious exploration missions (e.g., lunar and Mars), where replacement is not feasible
- Seek to establish global norms and standards that support interoperability, shaping commercial practices, and ensuring alignment with wider policy objectives

Defence Departments:

- Prioritise resilience, adaptability, and the ability to respond quickly to emerging threats in space
- See serviceability as a means to extend the operational life of critical satellites and reduce vulnerability to adversarial actions
- Emphasise responsiveness and operational flexibility—maintaining capability “at the speed of relevance” rather than waiting years for replacement satellites
- Invest in serviceable spacecraft to secure sovereign capabilities and reduce reliance on foreign supply chains

Enablers (not primary drivers)

Satellite Manufacturers & Technology Developers: Manufacturers are adapting to the trend by:

- Developing modular designs, plug-and-play interfaces, and service-friendly architectures
- Partnering with servicing companies (like Lockheed Martin, Orbit Fab, Astroscale, Northrop Grumman)
- Co-developing interconnect and docking standards

Their role is to supply the tools and platforms, but they’re reacting to operator and agency needs.

Indirect (but growing pressure)

Insurers and Regulators (Emerging influence): Insurers are interested in lowering risk exposure and may soon offer better premiums for serviceable satellites. Regulators are increasingly focused on space sustainability and may mandate serviceability (or at least deorbit capability) for future missions — especially in congested orbits.

Stakeholder	Motivation
Operators	Maximise ROI, enable mid-life upgrades, shorten replacement cycles
Agencies/Defence	Mission flexibility, cost savings, long-term exploration infrastructure
Manufacturers	Meet market demand, innovate on modularity and interfaces
Insurers	Risk mitigation, long-term asset insurability
Regulators	Sustainability, debris mitigation, orbit traffic management

3. Are Standards Helping, or Hindering?

Standards can be technical and non-technical. They are generally non-binding, taking the form of specifications, guidelines, or best practices, and can be developed by international or regional organisations, governments, and industry bodies. It is worth noting that many satellite providers develop "in-house standards" for their own products, but these are rarely shared to protect intellectual property. Such standards may include design, management, communication, data, safety, security, and sustainability.

Standards can be used to scale and de-risk serviceable spacecraft and can achieve industry-wide or product-wide standardisation if implemented correctly. They can help to achieve:

- Interoperability by facilitating interfaces between technology, platforms, and services
- Simplified designs, as manufacturers can design to a common specification rather than reinvent every interface
- Lower risk and cost as insurance and regulatory approval become easier with proven, standardised interfaces
- Promote market growth, as buyers (operators) know there will be multiple vendors for servicing/replacement
- Safety and sustainability: standardised behaviours for rendezvous, docking, disassembly etc. to reduce collision risk
- International collaboration that could help emerging ISAM markets grow.

Imagine if every satellite needed a custom servicing vehicle — that's where standards step in.

Conversely, standards could become obsolete or inadvertently stifle growth if they do not represent the state of the art. The legal meaning or status of standards also depends on how they are implemented, and a clear approach to integrating standards into legal and regulatory frameworks applicable to ISAM is key to realising any benefits.

Standards development points:

- How standards are currently implemented regarding space activity in different regulatory regimes and across various in-orbit operations (in particular, ISAM activities)
- Opportunities to use standards to promote market growth, by, for example, promoting international collaboration, market access, attracting investors, as well as driving safe and sustainable practices
- Consider how standards work in adjacent industries with some similar risks, such as aviation, to promote safety, sustainability, and growth.

3.1. National vs. International Standards

Should standards be national, international, or maintained by the industry? (Note: for a more in-depth view on the various standards, see the "Rendezvous Proximity Operations and Docking[iii]" paper, specifically section 5/table 1.)

The pros and cons are summarised below.

Approach	Pros	Cons
International (e.g., ISO, CCSDS)	- Promote global interoperability - Supports cross-border servicing - Reduces risk of obsolescence	- Very slow to develop - Hard to get agreement (especially among US, Europe, China, Russia)
National/Regional (e.g., NASA, ESA, JAXA)	- Faster to prototype and deploy - Strong government backing (e.g., mandates for government satellites) - Can lead market initially	- Risk of fragmentation - Risk of obsolescence if global standards later emerge and differ
Small-Scale Industry Standards (e.g., Consortiums like CONFERS, Orbit Fab's RAFTI)	- Agile, market-led - Practical, because it comes from active missions - Easier to iterate based on lessons learned	- Limited adoption without government buy-in - Risk of being "locked out" if international standards diverge

The Pros & Cons of each approach:

- "Light-touch", small-scale, industry-led standards will get technology flying fastest
- National standards will give the market a head start but risk isolation
- International standards are essential *long term* for sustainability, insurance, and commercial scaling.

The path being taken by many (e.g., Orbit Fab, Astroscale, Maxar) is to develop hardware now using practical standards, while engaging with international standards bodies to converge over time.

3.2. Emerging Standards

There are debates happening in several fora regarding standards for RPO and serviceability of spacecraft. The main standards in development are:

- **CONFERS Best Practices** for rendezvous and proximity operations (RPO) and servicing
- **ISO 24330** — RPO safety and interoperability
- **NASA OSAM interface work** — modular servicing hardware specifications
- **Space Sustainability Standards (ISO and UN COPUOS)** — will increasingly tie into servicing capability

3.3. Strategic Risks

If the space sector continues to rely on disposable, non-serviceable spacecraft, it risks locking itself into unsustainable practices, escalating costs, and missed opportunities for resilience and innovation. The rapid growth of satellite constellations, rising launch cadence, and the proliferation of debris mean that ignoring serviceability is not just a commercial risk, but an environmental and strategic risk for governments, operators, and manufacturers alike.

If a nation (or company) develops purely proprietary servicing interfaces or practices they:

- May *capture early market share*, but
- Risk being left behind when global operators, insurers, and regulators demand international compliance for debris mitigation, cross-servicing, and orbital traffic management

Short-term: **Get to market first with working, serviceable designs** — even if they are only partially standardised — and **influence the standards from a position of leadership.**

Long-term: **Global compatibility will prevail.**

3.3.1 How can Satellite Designs Evolve to Support ISAM?

- Move from monolithic architectures to **modular designs** with well-defined, standardised interfaces (mechanical, electrical, fluidic, and data)
- Introduce **design-for-serviceability (DFS)** and **design-for-recycling (DFR)** principles, ensuring subsystems can be replaced, upgraded, or repurposed in orbit
- To align with **space sustainability principals**, systems in serviceable spacecraft must be both serviceable (Designed for Serviceability, DFS), disassemblable (Design for Disassembly, DFD), and recyclable (DFR). These three principles are complementary: DFS defines the maintenance framework, DFD provides the means for safe removal or replacement, and DFR enables material recovery at end of life
- Incorporate features that are compatible with **robotic manipulation** and autonomous assembly, such as keyed connectors, blind-mate interfaces, and secure latching mechanisms
- Adopt **digital twin models** to simulate, verify, and validate servicing operations pre-launch, reducing uncertainty during real-world interventions

3.3.2 What are the Trade-offs?

- **Mass and complexity:** Adding serviceability features may increase initial spacecraft mass and design complexity, which could increase launch costs
- **Standardisation vs. customisation:** Committing to standard interfaces may constrain bespoke design choices, but creates scale economies and interoperability benefits
- **Upfront cost vs. lifecycle cost:** Serviceable spacecraft may be more expensive at the point of manufacture but offer long-term savings through extended lifetimes, reduced (satellite) replacement needs, and in-orbit upgrades
- **Operational risk:** Designing for servicing introduces new dependencies (e.g., availability of servicing providers), which must be balanced against the benefits of flexibility and resilience

3.3.3 The Benefits of Serviceable Spacecraft

- **Cost efficiency:** Extending satellite lifetimes and enabling in-orbit upgrades reduces the need for costly replacements and will reduce launch frequency
- **Sustainability:** Serviceability reduces the accumulation of orbital debris and enables recycling of mass already in orbit, aligning with global sustainability goals, specifically UN Sustainable Development Goal #9

- **Flexibility:** Operators can more rapidly respond to market shifts, new mission requirements, or emerging threats by upgrading or reconfiguring satellites in orbit
- **Resilience:** Systems designed for servicing can recover from failures and adapt to adversarial actions more effectively than satellites not designed for maintenance
- **Innovation:** A serviceable architecture creates opportunities for new business models, such as "capability-as-a-service" or in-orbit manufacturing, unlocking value across the sector

4. How will this be Achieved?

The technical feasibility of modular and serviceable spacecraft is increasingly supported by advancements across a range of technologies, including approach sensors and Guidance, Navigation and Control (GNC) systems, pose estimation algorithms, mechanical docking interfaces, refuelling interfaces, electrical connections, software protocols and materials. These developments are transforming how spacecraft could be designed, operated, and maintained in orbit, allowing for greater adaptability, sustainability, and cost-effectiveness throughout their lifecycle.

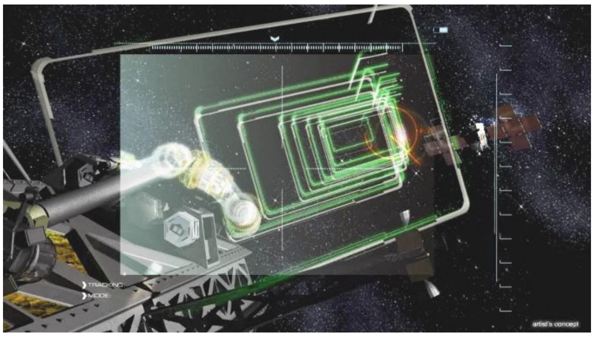
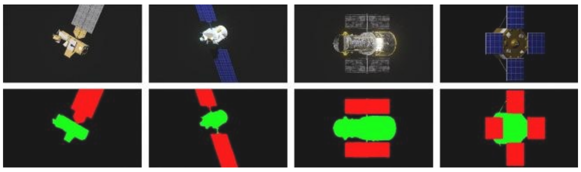


Image Credit: DARPA



Feature recognition for pose assessment

4.1. Technical Considerations for Serviceable Spacecraft

4.1.1 In-orbit Refuelling

In-orbit refuelling has progressed faster than other ISAM technologies and represents a cornerstone of the serviceable spacecraft ecosystem. It offers significant benefits including extended mission lifetimes, increased flexibility in mission planning, and reduced dependence on initial fuel loading. Refuelling capabilities open the door to more ambitious operations, including repositioning, de-orbiting, or redeployment of spacecraft, and support economic models based on in-orbit manufacturing and servicing. These capabilities also address issues such as launch mass constraints, complex design trade-offs, and time-to-orbit considerations, offering satellite operators a path to maximise return on investment.

A refuelling capability needs to consider:

Interfaces

- Fluid coupling design: Utilise a standardised, blind-mate refuelling valve, ideally conforming to protocols being developed by groups like CONFERS, NASA, or Orbit Fab's RAFTI (Rapidly Attachable Fluid Transfer Interface)
- Accessible location: Mount the refuelling port on an externally accessible, flat or slightly recessed surface to aid robotic docking or manual servicing

- Keyed alignment features: Ensure the interface has mechanical guides or keying features for proper orientation and alignment during docking

Propellant Tank Design

- Multiple fill/drain ports: Include dedicated fill and vent lines separate from main feed lines to thrusters/engines, enabling safe and efficient refuelling
- Flexible bladder or surface tension systems: Use propellant management devices (PMDs) like vanes, sponges, or bladders to ensure fuel collects near the tank outlet in microgravity
- Tank sizing and isolation: Consider tank segmentation or isolation valves, allowing partial refuelling or isolation of unused propellant volumes to reduce contamination risk

Thermal and Structural Considerations

- Thermal insulation: Protect refuelling ports and lines with MLI or active thermal control, especially for cryogenic or hypergolic propellants
- Mechanical load handling: Design the spacecraft and refuelling interface to handle reaction loads from docking/undocking and the mass shift associated with refuelling
- Radiation shielding: Protect sensitive fuel lines and valves from degradation by incorporating shielding or using radiation-tolerant materials

Safety and Contamination Control

- Leak detection sensors: Integrate pressure sensors or mass flow meters to verify successful refuelling and detect leaks
- Contamination seals: Use dual-seal designs or self-sealing valves to prevent outgassing or fuel leakage during dormant phases
- Isolation valves: Include redundant valves between the refuelling interface and tank to allow safing in case of fault

Autonomy and Servicing Compatibility

- Software-defined control: Support autonomous or ground-directed fuelling by implementing control software for valve sequencing, verification, and safety interlocks
- Docking target markers: Place visual fiducials or RFID tags near the refuelling port to allow robotic servicing systems to be guided into place
- Structural support near interface: Reinforce the panel or structure where refuelling occurs to support robotic interaction and prevent deformations

Propellant Type Considerations

- Cross-compatibility: Design with future propellant compatibility in mind—e.g., allow tank coatings, valves, and other elements to work with available propellants (e.g., xenon, hydrazine, butane)
- Alternative fuels: Consider emerging green propellants (e.g., AF-M315E, LMP-103S) that offer safety and performance benefits, especially if long storage or multiple refuellings are expected

Lifecycle and Operations Planning

- Refuelling cadence: Design fuel tanks for multiple refuelling events without degrading seals or valves
- Launch fill vs. operational fill: Consider launching partially empty to reduce mass and perform initial tank fill in orbit, if that aligns with launch and mission strategy
- Documentation: Include detailed interface control documentation (ICD) to enable third-party refuelling missions

4.1.2 Software

When designing a serviceable, repairable, or augmentable spacecraft, software interfaces and protocols must be considered—they are the digital glue that allows modular systems, new components, and external servicers to safely interact with the spacecraft. Here are some key considerations that should be accounted for:

Modular and Extensible Software Architecture

- Modular codebase: Implement a modular software framework where each subsystem or payload operates in a semi-autonomous fashion, communicating through defined Application Programming Interfaces (APIs). This simplifies the integration of new or upgraded components post-launch
- Plug-and-play compatibility: Support dynamic discovery and integration of new modules (e.g., hot-swapped sensors, comms payloads, or propulsion systems), providing USB-like behaviour in space systems
- Version control and rollback: Embed onboard versioning with the ability to roll back software updates or module firmware in case of incompatibility

Standardised Data and Command Protocols

- Interoperable protocols: Adopt standardised communication and control protocols such as CCSDS (Consultative Committee for Space Data Systems), CAN or SpaceWire, ensuring new components or servicing systems can understand and interact with the host
- Command abstraction layers: Use a high-level command abstraction so hardware-specific instructions are hidden behind a standard API (e.g., "Get power telemetry" rather than "read bus voltage on line 3")
- Future-proofing: Use extensible protocols (e.g., Protobuf, JSON with schema) that permit the addition of new data types or commands without breaking older implementations

Cybersecurity and Data Integrity

- Secure authentication: Implement robust handshake protocols (e.g., challenge-response, Public Key Infrastructure (PKI) based identity verification) before accepting software updates or servicing commands
- Integrity checking: Use checksums, digital signatures, and redundant storage for all updates and configurations to detect corruption or tampering
- Network segmentation: If multiple service modules or external systems are involved, implement logical data separation (akin to firewalls) between critical and non-critical systems

Fault Tolerance and Reconfiguration

- Redundancy awareness: Software should be designed to reconfigure the spacecraft's operational profile based on failed or replaced components (e.g., re-routing power paths, using backup comms links)
- Autonomous failover: Include decision trees for autonomous failover or fallback modes, especially when connection to the ground is lost mid-repair or augmentation
- Health monitoring agents: Use distributed diagnostic agents to continually assess subsystem status and report anomalies for onboard or external intervention.

Service Interface Compatibility

- Digital twin integration: Maintain a digital twin interface that mirrors the spacecraft's configuration, performance history, and service events, so that servicing agents (automated or human) can plan safe and effective interventions
- Robotic interface protocols: If robotic interaction is expected, follow data exchange protocols for pose estimation, actuation commands, and latching state (e.g., NASA's OSAM control protocols)
- Metadata tags for replaceable components: Design each module or drawer to report a standard metadata packet upon power-up, including part number, firmware version, operational status, and service history

Onboard Resource Management

- Dynamic resource allocation: Enable onboard scheduling software that can dynamically assign bandwidth, power, and computational resources as modules are added or removed
- Hot-Swap-ability: Data lines should support hot-plugging, allowing modules to be added or removed without requiring system reset or reboot. Systems should auto-detect and integrate newly connected modules, applying unique IDs and routing data accordingly
- Sandboxing of new systems: Initially operate newly installed components in a "sandbox" or limited mode until their performance and compatibility are validated

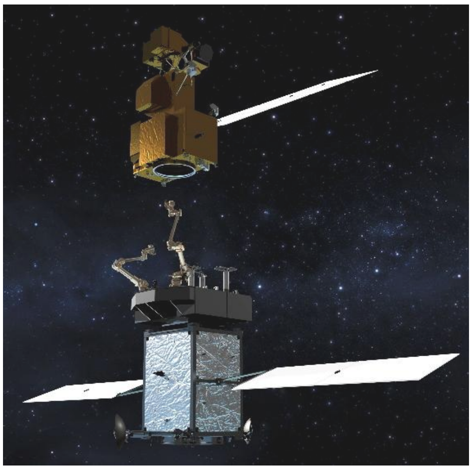
Ground Segment and Interface Support

- Remote patching and diagnostics: Support secure over-the-air updates (SOTA) with ground-based validation and rollback procedures
- Unified control interface: Use a standard command and telemetry interface for both new and legacy systems, simplifying mission ops even as the spacecraft evolves
- Simulation-ready environment: Ensure that all onboard interfaces can be emulated or simulated in software for pre-deployment testing or troubleshooting post-launch

Example Standards and Best Practices

- **NASA CFS (Core Flight System)**: Modular flight software framework with proven use in modular missions
- **ECSS-E-ST-70-41C**: European telemetry and telecommand standard
- **ROS 2 for Space Robotics**: Emerging standard for robotic spacecraft and servicers
- **CONFERS & ISO TC20/SC14**: Devising digital interface and command standards for servicing.

4.1.3 Robotic Manipulation and Assembly in Space



Robotic manipulation systems will be essential for in-orbit servicing. A promising approach includes standardised drawer-like modules that can be inserted or removed by robotic arms with minimal complexity. These systems benefit from concepts developed in other remote, harsh environments, such as aviation and subsea operations. Ensuring secure latching, alignment feedback/confirmation, and plug-and-play functionality are crucial for enabling autonomous or teleoperated maintenance and upgrades.

To promote interoperability and reduce integration complexity, NASA and its international partners have developed the International External Robotic Interoperability Standards (IERIS). These standards define common mechanical, electrical, and operational interfaces for robotic servicing and assembly tasks, ensuring compatibility across diverse spacecraft and robotic systems. Incorporating IERIS principles into future designs can significantly enhance cross-platform servicing capability and reduce mission risk.

Key items to consider:

Docking Interface Design

- Standardisation: Use docking interfaces that conform to industry standards (e.g., NASA's Soft Capture Mechanism, iBDM from ESA, or emerging commercial standards like those from CONFERS)
- Alignment Aids: Include visual fiducials, passive guide funnels, chamfers, and magnetic or mechanical alignment features to help spacecraft engage accurately
- Mechanical Latching: Ensure robust latching mechanisms with redundancy and clear positive feedback (e.g., latching indicators or status telemetry)
- Force/Torque Accommodation: Design interfaces to absorb minor misalignments or contact forces during docking using compliant or dampened components
- The AOCS systems of both the servicer and the client will need to understand the physical changes of the combined stack at capture and during operations (e.g., Centre of Mass and Moment of Inertia shifts) and if necessary, counteract any undesirable motion

Grasping and Handling by Robotic Arms

- Grasp Points: Provide standardised, reinforced grasp fixtures (e.g., grappling fixtures similar to those used on the ISS, or custom single-action interfaces for drawer-like modules)
- Keyed Orientation: Components should be keyed or asymmetrical so they can only be inserted in the correct orientation, reducing the need for robot vision complexity
- Structural Integrity: Ensure components can withstand manipulation forces during handling without damage—especially under microgravity conditions
- Materials: Certain materials interacting with each other could cause problems (e.g., cold welding, etc.)

- Thermal and Surface Considerations: Avoid glossy or thermally unstable materials in grasp areas—robots may use visual sensors or have thermal sensitivity
- Grounding: Generally, the docking process will accommodate potential differences between the spacecraft. It is feasible that a robot servicer could act on a spacecraft without having docked first and grounding in this scenario will have to be considered

Blind-Mate Connectors

- Tolerance Management: Use floating or compliant mounting for connectors so minor misalignments during insertion are automatically corrected
- Sequential Engagement: For electrical connectors, follow safe connection sequences: ground → data → power
- Fluid/Gas Couplings: Incorporate check valves or self-sealing features to avoid leakage, with cleanable or replaceable seals
- Insert/removal Forces: Traditional connectors often require significant insertion and extraction forces, which can exceed the torque limits of robotic arms in microgravity
    - Zero Insertion Force (ZIF) connectors can address this by using an actuation mechanism (e.g., a lever or cam) to engage contacts after the connector halves are mated, reducing insertion force to near zero. This design minimises mechanical stress, improves alignment tolerance, and is particularly suited for robotic servicing in space. Recent developments, such as Axon Cable's ZIF connectors for space-grade flat cables, aim to achieve TRL 6 for use in satellites and modular spacecraft

Autonomous Operations Support

- Visual Markers: Add AR tags, QR codes, 3D targets and/or fiducial markers that enable task and motion planning by robotic systems
- Telemetry & Feedback: Enable health and status telemetry for each docking attempt (e.g., force, vibration, successful latch), viewable by operators or used in closed-loop robotic control
- Modularity: Design systems that can be incrementally assembled or upgraded with standardised module shapes, connection points, and interface hierarchies

Safety and Fault Tolerance

- Failsafe Modes: Components should fail in a safe state if servicing is interrupted or aborted
- Emergency Release: Include features allowing emergency separation if a module becomes stuck or misaligned
- Cross-checks: Incorporate sensors (e.g., Hall effect, mechanical switches, current/voltage sensors) to confirm successful docking before power/data transfer

4.1.4 Advanced Propulsion Systems for On-orbit Manoeuvring

Whilst serviceable spacecraft themselves do not require advanced propulsion systems for precision manoeuvring during servicing and reconfiguration operations, it might be helpful to aid in RPO and ISAM operations. Such propulsion systems must support frequent ignitions/burns, high positional accuracy, and the ability to dock or undock components reliably.

Key considerations:

Long-range Approach and Transfer Manoeuvres

a. Efficient Main Propulsion:

- Use high-specific-impulse systems (e.g., electric propulsion) for long-duration orbit transfer or rendezvous manoeuvres
- Must balance delta-v capability with onboard power availability and thermal limits

b. Precise Orbital Phasing and Timing:

- Propulsion must be integrated with onboard navigation systems to perform time-sensitive burns for optimal phasing
- Trajectory planning must consider space traffic and conjunction risks when crossing orbital planes or altitudes, as well as fuel efficiency

c. Autonomous Navigation Integration:

- High-fidelity sensors (optical, lidar, RF, etc.) and flight software must coordinate with propulsion for on-the-fly corrections during transfer phases
- Autonomous collision avoidance capability is increasingly valuable

Mid-range Proximity Operations (~1 km to 10 metres)

a. Variable Thrust Capability:

- Ability to finely control thrust output becomes critical for closing distances slowly and safely
- Cold gas or throttleable chemical systems (e.g., H_2O_2, ADN monopropellants) are common for precise, responsive thrust

b. Redundancy and Fault Tolerance:

- All propulsion and RCS systems should include N+1 or better redundancy in case of valve or thruster failure
- Fail-operational behaviour is critical during RPO (rendezvous and proximity operations)

c. Low-Disturbance Manoeuvring:

- RCS systems must minimise plume impingement and contamination, especially near sensitive payloads or optical sensors on the target

Close-quarters Operations and Final Docking (<10 metres)

a. Fine Attitude and Translational Control:

- Must provide very low-thrust impulse (typically <1 mNs) for precise relative positioning
- 6DoF (six degrees of freedom) control is necessary — full translation and rotation capability in close approach

b. Thruster Layout and Placement:

- Reaction Control System (RCS) must avoid creating torques that can't be easily countered, e.g., a symmetric layout
- Placement must also avoid line-of-sight blockage to navigation sensors (e.g., cameras, lidars)

c. Plume Effects on Interfaces:

- Thruster orientation must avoid exhaust impingement on docking targets, thermal coatings, or sensors
- Consider self-contamination risks when firing in close proximity

d. Smooth Mode Switching:

- Must enable seamless transitions between propulsion control modes — from orbital burns to RCS micro-thrusting
- Autonomy software should recognise and manage docking phases (e.g., Approach → Hold → Dock → Retreat)

e. Thermal and EMI Compatibility:

- Ensuring propulsion systems do not interfere thermally or electromagnetically with sensitive systems, particularly when co-located near optical sensors or docking ports

Post-Docking Stability and Maintenance Operations

a. Docking Impulse Management:

- Systems must dampen and absorb residual momentum from the docking event
- Consider incorporating compliance (mechanical damping or soft-capture technology)

b. Station-Keeping and Control Postures:

- After docking, combined spacecraft must maintain attitude for power generation, thermal control, and communications
- Coordinated control between vehicles may be needed (e.g., Leader/follower control mode)

c. Propellant Management Systems:

- For long-lived servicing vehicles, consider in-orbit refuelling compatibility
- Include pressure regulation, isolation valves, and propellant gauging for extended missions

Optional Advanced Considerations:

- Chaser-target coordination protocols (e.g., Who controls attitude of each spacecraft during docking?)
- Multi-target serviceability — ability to detach, reposition, and approach new targets with minimal downtime
- Propulsion system modularity — replaceable propulsion packs or drop-in refuelling units

4.1.5 Autonomous Navigation and Control Systems

The design of autonomous Guidance, Navigation, and Control (GNC) systems is central to enabling safe, reliable, and precise servicing, docking, and modular reconfiguration of spacecraft. These systems must accommodate complex operational environments, manage highly dynamic proximity operations, and adapt in real-time to unforeseen conditions—all while maintaining mission assurance without direct human input.

Guidance System Considerations

Autonomous guidance systems must support multi-phase approach trajectories, encompassing orbital phasing, mid-range transfer, and terminal docking. This requires a mix of long-range path planning and fine control during close proximity operations:

- Trajectory segmentation: Guidance algorithms should support distinct operating modes for each phase, including Lambert arc planning for orbital transfers and Clohessy-Wiltshire or Hill's equations for terminal rendezvous
- Safety corridors and hold points: Trajectories should incorporate predefined approach cones, keep-out zones, and hold points to minimise risk of collision and enable time for diagnostics or plan updates
- Dynamic re-planning: Adaptive guidance is essential for responding to unexpected target manoeuvres, sensor drift, or debris interference. Autonomous re-planning algorithms should account for available fuel, target state uncertainty, and mission priorities

Navigation System Considerations

Accurate and robust state estimation is critical for autonomous proximity operations. Navigation systems must fuse data from diverse sensors to maintain reliable situational awareness across large dynamic ranges:

- Sensor fusion architecture: Combine GNSS, star trackers, and Inertial Measurement Units (IMUs) for far-range navigation; radar, LIDAR, and visual odometry for mid-range; and cooperative optical targets (e.g., AprilTags or reflectors) for close-in navigation. Extended or Unscented Kalman Filters are typically used for sensor fusion
- Redundancy and robustness: Navigation subsystems should include redundancy for mission-critical sensors and fault detection to mitigate erroneous or drifting data sources. Passive or cooperative features on the target spacecraft—such as fiducials, beacons, or attitude telemetry—can greatly enhance navigation robustness
- Cooperative aids on host spacecraft: Designers should embed clear visual or reflective markers, shared timing or ephemeris interfaces, and well-defined docking targets to facilitate precision navigation by a servicer spacecraft

Control System Considerations

The control subsystem must manage spacecraft attitude and translational motion simultaneously, typically within a six-degree-of-freedom (6DOF) control regime:

- Fine actuation and impulse control: Attitude adjustment and low-thrust systems are essential for sub-centimetre positional control and sub-degree alignment accuracy during docking or servicing
- Hot redundancy and fault tolerance: Control systems should allow for fallback configurations or safe modes in the event of actuator failure, particularly during final approach and docking sequences
- Soft docking and contact dynamics: Algorithms must dampen out oscillations and handle misalignment through compliant control laws or cooperative docking mechanisms that absorb minor impact energy

Autonomous Behaviour and Fault Handling

To support full autonomy in proximity operations, GNC software must manage operational modes and respond to anomalies without human oversight:

- State-based control: Autonomy software should implement a deterministic state machine or behaviour tree architecture, sequencing modes such as approach, inspect, dock, latch, service, and retreat
- Real-time contingency response: The spacecraft must be able to detect and respond to off-nominal scenarios—such as target drift, misalignment, or sensor faults—by aborting manoeuvres, backing away, or entering a safe-hold mode
- AI and adaptive learning (emerging): Future systems may integrate machine learning techniques for improving pose estimation or tuning control laws based on real-time telemetry, simulation-trained policies, or past mission data

Verification and Standards

Given the complexity and safety-critical nature of autonomous GNC, rigorous verification and validation is essential:

- Hardware-in-the-loop (HIL) testing: GNC subsystems should be validated using dynamic testbeds that simulate spacecraft dynamics and sensor responses in real-time
- Digital twins and scenario simulation: Mission designers should use high-fidelity digital models to run Monte Carlo simulations across a wide range of failure modes, environmental conditions, and target behaviours
- Standards and protocols: GNC software and data interfaces should align with emerging in-orbit servicing standards (e.g., NASA's xGDS, ESA OPS-SAT APIs, ISO 24354-1 for proximity operations) to ensure future interoperability and upgradeability

4.1.6 Energy Storage and Power Systems

In spacecraft design, the selection of energy storage technology and chemistry depends on the mission profile. Lithium-ion technologies such as lithium iron phosphate ($LiFePO_4$) (LFP) and cobalt-free chemistries, together with solid-state batteries, offer safer and longer-lasting energy solutions. These options reduce replacement frequency and improve sustainability during the operations phase.

At the same time, improvements in overall sustainability depend on the implementation of DFS, DFD, and DFR strategies combined with innovations in engineering and green chemistry. In high-radiation environments, adaptive shielding and radiation-hardened materials are crucial for preventing capacity loss. Systems must also include diagnostics and autonomous fault detection for dynamic energy management.

A DFS approach ensures that power systems incorporate in-orbit diagnostics, autonomous fault detection, and standardised modular interfaces, allowing spacecraft to optimise power distribution dynamically as battery performance degrades. In high-radiation environments like GEO and deep space, ionising radiation accelerates electrolyte breakdown, reducing battery capacity. (See Impact of space radiation on lithium-ion batteries: A review from a radiation electrochemistry perspective[iv]). To counteract this, radiation-hardened materials and adaptive shielding have been developed, leading to improvements in energy retention over extended missions.

DFD principles are not yet widely implemented in current aerospace energy storage and power systems. Traditional adhesive and welded assemblies make disassembly and component recovery difficult. Future space-grade designs should adopt robot-friendly architectures and detachable structural components, using accessible fasteners, connector routing for autonomous handling, and standardised geometries for machine vision and robotic gripping. Beyond mechanical design, material advances such as dissolvable binders and reversible supramolecular electrolytes offer non-destructive disassembly options. These technologies could enable safe in-orbit servicing and post-mission material recovery without compromising structural integrity during operation.

From a DFR perspective, lithium-ion systems using LFP or other cobalt-free cathodes can achieve over 95% recyclability through terrestrial hydrometallurgical or direct recycling processes, as demonstrated by UK pilot programmes led by Altilium Clean Technology and the UK Battery Industrialisation Centre (UKBIC). (News: Altilium and UKBIC announce successful production of UK's first EV battery cells made from recycled materials[v]) (Paper: A review of lithium-ion battery recycling for enabling a circular economy[vi]), supporting a closed-loop material recovery process. Further research is required to assess how such recycling processes could be adapted and validated for space applications.

Recent international efforts reflect a shift toward mandatory serviceability standards (e.g., ECSS-U-AS-10C Rev.2, 9 February 2024). By integrating DFS, DFD, and DFR principles into the emerging regulatory framework, future space missions can improve energy efficiency, reduce environmental impact, and ensure long-term power reliability in extreme space conditions.

System Design Considerations

- Modularity and Accessibility: Power units (e.g., batteries or capacitor packs) should be designed as independent modules with standardised mechanical and electrical interfaces to enable robotic replacement or augmentation
- Hot-Swap-ability: Power modules must be designed to support live disconnect/reconnect without damaging electronics or triggering faults, often through sequencing (e.g., ground-first, power-last contact design)
    - Consideration should be given to how power is maintained (if required) during a battery swap. Space for a new battery may need to be considered, unless power can be provided by another source, e.g., a servicer spacecraft
- Energy Scalability: Architecture should support the addition or removal of energy modules to accommodate changing power requirements as the spacecraft is augmented or serviced
- Redundant and Isolated Power Paths: Multiple independent power buses (or cross-strapped systems) ensure that individual module or line failures do not cascade through the system
- Radiation Hardening and Thermal Management: Use radiation-resistant chemistries and shielding to prevent electrolyte breakdown and capacity loss; include integrated thermal regulation (e.g., phase change materials) to maintain optimal operating temperatures

Module Design Considerations

- Design for Serviceability (DFS): Incorporate diagnostic sensors for in-orbit health monitoring (voltage, temperature, capacity, cycle count) and fault isolation, typically through an advanced Battery Management System (BMS) that enables pre-emptive maintenance or autonomous swap-out

- Design for Disassembly (DFD): Employ modular architectures and standardised fastening or connector systems that allow non-destructive removal and replacement of components Interfaces should be accessible for robotic manipulation, using keyed alignments, low-insertion-force connectors, and verified latching mechanisms to ensure safe handling and reassembly in orbit
- Design for Recycling (DFR): Use of green chemistries with high recovery potential, advanced recycling processes, and modular packaging that enables safe and efficient disassembly in-orbit or on Earth
- End of life: Design energy storage systems to minimise risk of break-up due to on-board energy sources, in compliance with emerging space sustainability standards. Beyond safety, end-of-life plans should focus on refurbishing components, remanufacturing in space, and recovering materials for reuse. These measures support in-orbit servicing, assembly, and manufacturing (ISAM) activities and reduce dependence on materials launched from Earth

Implementation Challenges and Mitigation

The hostile space environment and the need for remote, autonomous intervention create several design challenges:

- Degradation Over Time: Ionising radiation, thermal cycling, and charge/discharge cycles accelerate battery wear, particularly in GEO and interplanetary environments. Mitigation strategies include:
  - Use of radiation-tolerant green chemistries (e.g., LFP or cobalt-free systems) complemented by advanced variants such as solid-state and lithium-sulphur chemistries with superior longevity and radiation tolerance (aligns with DFR)
  - Adaptive Battery Management Systems (BMS) that dynamically balance loads and reconfigure arrays (central to DFS)
- **Safe Handling and Integration**: Autonomous robotic manipulation of power units introduces risks related to arcing, thermal runaway, and connector misalignment. This is mitigated through:
  - Interlock systems and software-controlled switching to isolate power paths during connection/disconnection (required by DFD)
  - Mechanical keying and alignment guides for robotic mating, with sensor-based confirmation of correct connection
- **Distributed Power Architectures**: Instead of relying on a central power source, modular spacecraft may use distributed sources (e.g., power-per-module), requiring:
  - Smart power distribution units (PDUs) with local fault protection, telemetry, and communication links
  - Common voltage standards and conversion protocols for compatibility across modules
- **Limited Diagnostic Access**: Unlike terrestrial systems, space-based energy storage cannot be physically inspected during operation. Mitigation requires:
  - Comprehensive sensor suites providing real-time health metrics (voltage, temperature, impedance)

  - Predictive algorithms for remaining useful life estimation
  - Redundant telemetry paths to ensure data availability during degradation events
- **End-of-Life Disposal and Material Recovery:** Decommissioned energy storage units pose debris risks and represent significant embodied value. Challenges include:
  - Safe passivation of residual energy to prevent thermal runaway or rupture
  - Lack of established infrastructure for in-orbit disassembly, sorting, and material processing
  - Economic trade-offs remain unclear between Earth return and in-space recycling
  - Mitigation strategies involve designing for controlled discharge, standardised disassembly sequences, and future integration with ISAM facilities
- **Supply Chain and Standardisation**: Long mission durations and infrequent servicing opportunities demand high reliability and component interoperability:
  - Pre-qualified component databases and flight heritage tracking
  - Industry-wide interface standards to enable cross-platform compatibility
  - On-orbit spare depots or servicer-carried inventory for critical components

4.1.7 Advanced Materials Enabling Serviceability and Modularity

Radiation-resistant, thermally stable, and lightweight materials are available for use in modular and serviceable spacecraft. Such materials provide long-term durability and adaptability in extreme space environments. An approach incorporating DFS principles, prioritises materials that enable in-orbit repairs, structural adaptability, and prolonged mission lifetimes. Recent advancements in polymer-ceramic composites have demonstrated enhanced resistance to space radiation (Paper: Radiation and electrostatic resistance for ultra-stable polymer composites reinforced with carbon fibres[vii]), significantly reducing material degradation compared to conventional aluminium alloys. Additionally, multi-functional coatings with thermal emissivity control have improved temperature regulation by up to 40%, minimising the effects of extreme thermal cycling on spacecraft components (Paper: Development of variable emissivity coatings for thermal radiator[viii]).

From a Design for Recycling (DFR) perspective, integrating self-healing materials and recyclable metal matrix composites enhances structural integrity while reducing waste. Self-healing polymeric materials embedded with microcapsules have shown the ability to recover some mechanical strength after micrometeoroid-induced fractures, reducing the need for complete component replacements. The adoption of modular panelling systems, which use standardised and detachable composite layers, further supports recyclability and facilitates the replacement of damaged sections without full structural overhauls. By embedding DFS and DFR principles into spacecraft material design, future missions can achieve greater sustainability, lower maintenance costs, and enhanced resilience against harsh space conditions.

Key Considerations:

- Radiation and Thermal Resilience: Materials must withstand ionising radiation, UV exposure, and extreme thermal cycling. Radiation-resistant polymers, ceramic matrix composites, and aluminium-lithium alloys are increasingly preferred due to their lower degradation rates and long-term mechanical stability

- Surface Treatments for Durability and Handling: Non-stick coatings (e.g., fluoropolymer-based) or anodised surfaces may be required to reduce binding, galling, or seizing of contact points, especially for parts expected to be robotically unlatched or re-mated. In addition, low-outgassing surface finishes are vital to preserve optical and thermal systems
- Mechanical Compatibility for Repeated Mating: Surfaces at mechanical interfaces (e.g., drawer slides, fasteners, and blind-mate connectors) must be designed for repeated engagement without material transfer, micro-welding, or abrasion. Hardened wear surfaces, lubricious coatings (e.g., Molybdenum Disulfide, MoS_2, or Titanium Nitride, TiN), and composite bearing materials can extend mechanical life
- Thermal Emissivity Control: Multi-functional coatings with variable or controlled emissivity support active thermal regulation, particularly valuable in modular systems where heat distribution may vary after upgrades or module changes
- Material Pairings: Materials in mechanical contact must be selected with galvanic compatibility and thermal expansion differences in mind, especially when operating across wide temperature swings. Where required, appropriate isolation layers, gaskets, or compliant materials should be used to prevent welding, cracking or joint fatigue

Sustainability and Long-term Operations

Designing for long-term operations and end-of-life recovery requires attention to material recycling, identification, and modularity:

- Design for Recycling (DFR): Using single-material components, avoiding composite layering where not essential, and incorporating RFID tagging or embedded identification markers can facilitate automated identification and sorting during disassembly or recycling
- Self-Healing and Smart Materials: New materials such as self-healing polymers, microcapsule-infused coatings, or shape-memory alloys provide enhanced resilience by autonomously recovering structural integrity after minor damage (e.g., micrometeoroid impacts), extending component lifetimes and reducing servicing frequency
- Biological and Combustible Materials: Sustain Orbit's exploration of biologically derived materials, such as wood or biodegradable plastics, represents a novel approach. These materials offer RF transparency, full combustion on re-entry (reducing orbital debris), and potential for closed-loop recycling via bioreactors or in-space processing units

Interface-specific Challenges

Particular care must be taken at physical interfaces between modules:

- Binding and Stiction: Materials used at docking faces or actuator interfaces must avoid cold welding and static friction, which can be mitigated using engineered surface texturing or application of dry lubricants
- Cracking and Fatigue: In regions subjected to stress concentration or repeated thermal cycling (e.g., latches, hinges), the use of fatigue-resistant alloys or toughened composites is recommended
- Cleanliness and Contamination: Material selection should consider susceptibility to contamination and its potential effects on servicing (e.g., obscuring fiducial markers or compromising seals). Use of anti-fouling coatings and easily cleanable finishes can help

By integrating advanced materials, appropriate surface finishes, and sustainability-focused design principles, serviceable spacecraft can achieve greater reliability, support robotic and autonomous operations, and minimise long-term environmental impact.

4.2. Improved SDA

Enhanced SDA systems are essential for supporting servicing operations. European company Ecosmic offers novel approaches to SDA, and partnerships with such organisations can enrich the capabilities of future servicing architectures.

Given the high value of spacecraft, the need to monitor and verify successful servicing is paramount, and high accuracy SDA can support this.

4.3. On-orbit Verification and Validation (V&V)

On-orbit testing is required to verify new systems and upgrades. Dedicated orbital testbeds can allow for real-time V&V of components in space, beyond what ground testing can simulate. This will accelerate innovation while helping to provide mission assurance.

Considerations for on-orbit V&V:

Integrated Health Monitoring and Diagnostic Systems

- Pre-servicing Baselines: Establish a detailed pre-servicing baseline of the spacecraft's health, including telemetry profiles, performance characteristics, and subsystem configurations. This allows comparison before and after intervention
- Built-in Test (BIT) Systems: Design each subsystem—particularly those that may be repaired, replaced, or augmented—with self-test capabilities that can be triggered post-servicing to validate correct operation
- Redundant Sensors: Use dual or triple-redundant sensors for critical parameters (e.g., power flow, attitude, temperature, structural strain) to independently validate the integrity of the serviced components

Digital Twin and Ground-based Simulation

- Digital Twin Integration: Maintain a high-fidelity digital twin of the spacecraft on the ground. After servicing, sensor data can be compared against predicted outcomes from the twin to detect anomalies
- Model-based Verification: Use closed-loop simulation models (including GNC, thermal, and power subsystems) to simulate in-situ behaviour and validate updates from a systems-level perspective

Servicing Confirmation Protocols

- Positive Latching & Dock Confirmation: Mechanically serviced components (drawers, fuel connectors, tool interfaces) should have embedded sensors that confirm secure latching, alignment, and connectivity. Include telemetry flags for successful engagement
- Blind-Mate Interface Status: Electrical, optical, and fluidic connectors should include indicators or sensors confirming full mating, signal integrity, and, for fluids, leak-tight seals

Post-servicing Functional Test Procedures

- Stepwise Validation: Validate basic functions first (e.g., power routing, comms handshake), then perform higher-level operations (e.g., payload activation, attitude adjustments)
- Isolated Subsystem Tests: Allow isolated reactivation of serviced systems so faults can be traced and diagnosed without affecting the full system
- Latency-Aware Sequencing: Build-in wait states and checkpoints in post-servicing command sequences to account for remote operations, latency, and fault investigation if anomalies arise

Secure and Authenticated Configuration Management

- Version Control for Firmware/Software: If new software or configuration data is uploaded during servicing, include secure checksum and version validation before activation
- Command Authentication: Validate that only authenticated commands (from verified servicing agents) can change operational parameters or reconfigure modes

Structural and Thermal Validation

- Non-Destructive Testing (NDT) Techniques: Consider embedding acoustic or vibration sensors to detect signs of stress, delamination, or microcracks post-servicing—especially near mechanical interfaces
- Thermal Profiling: Monitor for abnormal heat dissipation patterns in newly serviced modules, as mismatches in conduction/emissivity might indicate poor attachment or unexpected electrical load

Visual and Situational Awareness

- Onboard Cameras & External Inspection: Use servicing spacecraft or the client spacecraft's own cameras to visually inspect completed operations. AI-based image analysis can flag anomalies
- SDA Integration: Use external sensors (ground-based or on-orbit) to verify the orbital configuration, orientation, and behaviour of the spacecraft post-servicing

4.4. Standardised Interfaces and Protocols

The widespread adoption of international standards for mechanical, electrical, data, optical, and fluidic interfaces is critical for the success of serviceable spacecraft. These standards must include precise definitions for dimensions, tolerances, connector types, and operational protocols. Much like ISO shipping containers revolutionised global logistics, these modular standards would simplify payload integration, promote interoperability, and reduce integration costs. Several satellite manufacturers are working to implement a "platform-as-a-service" model, allowing customer payloads to be quickly integrated and validated through digital twin simulations, improving testing efficiency and reducing turnaround times.

What standardised interfaces are most needed to promote spacecraft servicing?

Mechanical Mounting and Module Form Factors

- **Rationale**: Physical compatibility is the first barrier to modularity and servicing.

- **Focus Areas**:
    - Standard drawer dimensions (e.g., U-shaped modular bays, CubeSat-like scaling)
    - Latching, keying, and retention mechanisms for robotic manipulation
    - ISO-style fastener patterns or kinematic mounts to enable precise alignment

Electrical and Data Connectors

- **Rationale**: Interoperability in power distribution and data exchange is essential for plug-and-play servicing.
- **Focus Areas**:
    - Blind-mate electrical connectors with staged contact sequencing (ground → data → power)
    - Hot-swap-capable connectors with back-drivable force limits
    - Bus architectures for power (e.g., 28V, 100V) and data (e.g., SpaceWire, Time-Triggered Ethernet, SpaceFibre)

Fluid and Propellant Transfer Interfaces

- **Rationale**: Enables refuelling, thermal fluid exchange, or chemical replenishment
- **Focus Areas**:
    - Cryogenic- and pressure-rated fluid quick-disconnects
    - Non-proprietary refuelling ports (inspired by Orbit Fab's RAFTI)
    - Leak detection and shut-off protocols embedded in interface specifications

Software and Communications Protocols

- **Rationale**: Software interoperability and autonomy require shared digital standards.
- **Focus Areas**:
    - Discovery and handshake protocols (e.g., Open-RMF for robotics, adapted for space)
    - Common telemetry schema for diagnostics and servicing operations
    - Command and control APIs for servicing vehicles

Robotic Tooling and Graspable Features

- **Rationale**: Enables robotic capture, assembly, and repair with minimal adaptation.
- **Focus Areas**:
    - Standardised grapple fixtures, fiducials, or passive alignment aids
    - Visual and tactile markers for autonomous manipulation
    - Force/torque thresholds and compliance strategies

5. What do Serviceable Spacecraft Need?

5.1. Modular Spacecraft Components and Interfaces

Modular spacecraft architectures rely on standardised components that enable flexible integration, repair, and upgrading in orbit. A widely supported concept is the use of “drawers” or modular trays that contain discrete functions or subsystems—designed for easy insertion, removal, and replacement. These drawers should be engineered to support a range of functions, from power management and generation to payload hosting, and be dimensioned to accommodate the largest practical module used in a typical mission. To ensure safe, reliable operation in space, drawers should be keyed for one-way insertion and feature a single-point grab surface for robotic handling. Precision alignment and secure latching mechanisms are critical to ensure that all data, power, and fluid connectors blind-mate correctly during robotic servicing.

As noted earlier, key drawer characteristics for standardised modular design should include:

- Mechanical design: Keyed orientation, outer robotic grab point, blind-mate connectors
- Docking and feedback: Auto-latching with positive confirmation of connection
- Electrical interfaces: Hot-swappable connectors with contact sequencing (Ground → Data → Power)
- Fluidic/gaseous interfaces: Leak-proof sealing and pressure-safe mating during docking

By designing with these characteristics, modular spacecraft can enable rapid reconfiguration and minimise servicing complexity.

5.2. Servicing Infrastructure: On-orbit Platforms and Robotic Arms

Servicing modular spacecraft does not necessarily require complex robotic systems like the Canadarm. Instead, simpler mechanisms—similar to robotic tape autoloaders used in data centres—can be employed. These systems involve a mobile carriage or rail that moves across the spacecraft’s surface, using linear actuators to insert or retract modules from designated slots. Such an approach reduces mechanical complexity, increases reliability, and lowers the cost and mass of the servicing system. The concept is particularly suitable for standardised modular formats and allows for efficient upgrades or component swaps using semi-autonomous servicing platforms.

Future on-orbit platforms might integrate this infrastructure into a dedicated servicing bay or depot architecture. These depots could support various customer spacecraft and modules with shared tools and robotic capabilities. This infrastructure could also be adapted for logistics activities such as fuel resupply or data storage module swap-outs, increasing spacecraft longevity and mission flexibility. Design considerations for these systems must include compatibility with both active and passive spacecraft, automation readiness, and fail-safes for module handling in zero-gravity environments.

5.3. Power, Data and Communication Architecture

A unified, modular approach to spacecraft bus systems is necessary to support plug-and-play architecture. Power and data buses must be hot-swappable, support automatic recognition of new modules, and facilitate reconfiguration of networks as modules are removed or replaced. This architecture should resemble modern USB or Ethernet-based plug-and-play systems on Earth, allowing for distributed control and subsystem interoperability across multiple manufacturers.

Future buses should also be expandable, enabling the connection of additional modules in orbit to grow capability dynamically.

Communication systems should support both intra-spacecraft data sharing and external communication with ground systems or peer satellites. This includes integrated diagnostics, cross-module telemetry routing, and fault isolation. Optical interconnects may be used for high-speed internal links, and cross-module compatibility for bandwidth-intensive payloads like imaging sensors or compute nodes is essential. Secure communication protocols should also be standardised to protect sensitive module-to-module or module-to-ground data transfer.

5.4. Ground Segment and Control Systems

As spacecraft modularity increases, ground control systems must evolve to manage increasingly dynamic and complex configurations. Traditional command and telemetry frameworks need to support module-level configuration and tracking, enabling operators to address and manage individual modules, "drawers" or subsystems. A modular architecture also supports the potential for edge computing in orbit, shifting some autonomy and decision-making away from the ground segment. This requires robust monitoring and control interfaces for fault detection and module health analytics.

Emerging technologies like optical communication (e.g., Tesat Spacecom's LaserComm) offer high-throughput links between spacecraft and ground stations, addressing the bandwidth challenges associated with modular and upgradeable satellites. Optical systems are especially promising for data-heavy applications such as in-orbit AI processing or Earth observation. Integration of these links with intelligent ground segment platforms will allow for the remote provisioning, activation, and performance tuning of individual modules in real-time.

5.5. Power Management and Energy Storage

Power management in modular spacecraft must prioritise distributed architectures over centralised power systems. Autonomous energy balancing between modules ensures mission resilience, particularly when new modules are added or old ones degrade. Recent work in decentralised power distribution has demonstrated significant efficiency gains, enabling load sharing, fault isolation, and redundant power routing. Modules should be capable of contributing to or drawing from shared energy buses, with embedded diagnostics to detect failures and optimise battery charge/discharge profiles in real time.

Innovations in energy storage systems further enhance modularity. High-voltage, solid-state batteries are being developed that have the potential to extend mission duration and withstand space conditions. Tandem solar cell technologies show promise for increasing conversion efficiency, potentially achieving over 30% conversion efficiency even under suboptimal lighting conditions. Meanwhile, phase-change thermal regulation materials embedded in energy systems maintain optimal performance temperatures, reducing battery degradation. These developments, coupled with the adoption of green and high-recovery chemistries (e.g., LFP, cobalt-free systems) and high-longevity variants (solid-state, lithium-sulphur), support a more sustainable, long-lived spacecraft ecosystem. Realising this vision requires integrating DFS, DFD, and DFR principles from the design phase through end-of-life, ensuring that energy systems are not only technologically advanced but also serviceable, disassemblable, and recoverable throughout their operational lifecycle and beyond.

6. References

OECD — Space Sustainability
The OECD projects (Space Forum) emphasise that the accumulation of space debris risks making orbits unusable, which leads to sustainability being a strategic requirement for maintaining operations, not just meeting rules. OECD

Space Sustainability Rating (SSR)
SSR is a voluntary framework explicitly designed to incentivise operators to embed sustainability in mission design and operations, by publicly rating missions on sustainability metrics beyond minimal compliance. spacesustainabilityrating.org

NASA — Space Sustainability Strategy (2024)
NASA's strategy treats sustainability as a guiding principle for investment decisions, mission planning, and public reporting, not just as a box-checked regulatory requirement. NASA

ESA — Zero Debris Charter / ESA Sustainability Principles
ESA's own corporate guiding principles and charter show that sustainability is part of its mission identity, not only something to comply with. ESA's objectives for Zero Debris by 2030 and Corporate Sustainability underline this operational need. ESA

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[i] First study to examine environmental impact of deorbited satellites | University of Southampton

[ii] **UNOOSA — Guidelines for the Long-Term Sustainability of Outer Space Activities**
These guidelines declare that sustainability is fundamental to space activities and call on nation states and commercial operators to integrate sustainable practices throughout mission lifecycle, not just to fulfill regulatory obligations. unoosa.org

[iii] **Satellite Application Catapult – Digital Library**
A report setting out the methodologies and strategies needed for effective rendezvous and proximity operations and docking (RPOD) and in-orbit servicing, assembly, and manufacturing (ISAM), supporting both sustainability and resilience in space. Rendezvous Proximity Operations and Docking

[iv] Impact of space radiation on lithium-ion batteries: A review from a radiation electrochemistry perspective
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